Universidad del País Vasco Euskal Herriko Unibertsitatea

Análisis de inestabilidades en acantilados costeros del País Vasco e Italia como base para el desarrollo de estrategias de protección y gestión sostenible

Jon Ander Clemente Momoitio

PhD Thesis – 2022

Análisis de inestabilidades en acantilados costeros del País Vasco y Liguria como base para el desarrollo de estrategias de protección y gestión sostenible

Jon Ander Clemente Momoitio

PhD Thesis – 2022

Dirigida por Tomás Morales Juberías y Jesús Ángel Uriarte Goti

“La verdadera grandeza de la ciencia

acaba valorándose por su utilidad”

Gregorio Marañón

Agradecimientos – Acknowledgements - Esker onak

Ha llegado el momento de escribir este apartado, el principio del documento que reúne los últimos tres años de trabajo y esfuerzo para llegar hasta aquí, para presentar esta tesis doctoral. Es difícil a veces escribir cómo te sientes respecto a un trabajo cuando acaba, pero en este caso es muy fácil, porque todo el proceso ha sido sencillamente perfecto. Sé que por desgracia la mayoría de doctorandos y doctorandas no pueden decir lo mismo, que las situaciones son complicadas y que hay mil fases distintas de montaña rusa, en las que el límite entre dejarlo y seguir es una fina línea. En este caso, desde mi experiencia, solo puedo dar las gracias tanto al apoyo dentro de la universidad como desde fuera, ya que siempre me he visto escuchado y aconsejado de la mejor de las maneras, tanto personal como profesionalmente, y me ha permitido disfrutar al máximo de esta experiencia, por ello, ¡gracias infinitas a todos!

En primer lugar, agradecer a Tomás, que cuando tenía dudas de cómo actuar después de acabar el grado, en ese momento en el que no sabes a dónde ir ni qué hacer, confiara en mí para realizar el máster primero y el doctorado después, apoyando siempre cada decisión y aclarando cada duda en el camino. De verdad que no podría haber tenido un director mejor, y no solo eso, realmente empezaste como director, y después de estos 3 años eres mucho más que eso, y si hoy en día soy investigador y estoy presentando mi tesis doctoral, es sin duda en gran medida por ti.

Como no podía ser de otra manera, la otra pata de este banco, mi codirector, sin el que hubiera sido imposible realizar esta tesis doctoral, eskerrik asko Jesus benetan. Porque desde el TFG hasta hoy no has dejado de apoyarme, escucharme, entenderme y saber qué necesitaba en cada momento, y por estar siempre que ha hecho falta. ¡Además, está claro que, aunque se dice que el alumno suele superar al maestro, a veces, y en este caso en las figuras, sigue quedando mucho camino por recorrer, pero algún día llegará!

Por supuesto agradecer a mis compañeros del doctorado, a Eñaut, siempre apoyando en cada tema técnico, aclarando cualquier duda, y que es un referente sin duda para cualquiera que quiera ser investigador. A Martín, porque es difícil a veces realizar un camino sin gente que viva lo mismo que tú y que te entienda, y que viva con pasión el mundo de la investigación. A Zuriñe, porque compartir lo que piensas a veces es más importante que conseguir el resultado que buscas, y porque el trabajo también necesita sus momentos de desconexión.

No podían faltar todas las personas que me han ayudado, dando sus consejos y apoyo como Iñaki, Laura, Ane, Aranburu, Bodego, Murelaga, y todos los profesores que han dedicado su tiempo a aclarar mis dudas, a confiar en mí para hacer presentaciones, charlas, prácticas o simplemente para ayudar en lo que hiciera falta, benetan eskerrik asko bihotzez.

Agradecer de fuera de la universidad a Asier Hilario, director científico del Geoparque de la Costa Vasca, su confianza para realizar el trabajo de fin de máster que ha desembocado en esta tesis doctoral, y por atender las dudas y aportar la información necesaria siempre que la he necesitado.

Grazie anche a Daniele, sei una fonte di ispirazione per chiunque voglia dedicarsi alla ricerca, viaggiare in missione per il mondo, godersi ogni secondo. Grazie per l'opportunità di conoscere Roma, di godere con voi dell'ISPRA, di fare ricerca al di là della mia università. Non potrò mai ringraziarti abbastanza.

Grazie anche a Franz, Alessandra e Lele, per la spettacolare missione in Liguria, per avermi fatto assaporare cosa sia una missione di ricerca in Italia e per la grande esperienza che mi hanno regalato. Non vedo l'ora di fare altre missioni e ricerche insieme in futuro, è stato un vero piacere.

Infine, grazie a Francesco, a Chiara, a Luca, a tutti coloro che mi hanno aiutato all'ISPRA in qualche momento, che mi hanno dato la possibilità di conoscere modi diversi di lavorare, di capire che i legami di ricerca si possono consolidare anche se sono lontani.

No puedo olvidarme de vosotros, aita, ama, tato, habéis sido, sois y seréis un pilar fundamental para cualquier cosa que haga, y esta tesis doctoral no ha sido menos. Gracias por apoyarme en cada decisión que he tomado, por ayudarme cuando lo he necesitado y por orientarme cuando la decisión no parecía la mejor. Me habéis ayudado infinitamente a llegar hasta aquí, hasta el día en el que presento esta tesis doctoral, y sin vosotros habría sido imposible.

Por último, no podía faltar mi otra mitad en cada decisión que tomo, en cada duda que me surge o en cada momento difícil, gracias Tania. Gracias porque todo este proceso no habría sido posible sin ti, desde el grado, el máster y esta tesis, tus consejos, tu apoyo y el saber que siempre estabas ahí ha sido fundamental en todos los sentidos. Gracias también por esos meses inolvidables en Roma, por ese viaje increíble y por todo lo que nos queda por vivir después de esta tesis doctoral.

A todos los que me habéis ayudado en este camino en los últimos tres años, gracias de corazón.

Índice de la tesis doctoral

1. Introducción

Entorno playero de la Costa Vasca: contexto de estudio

1. Introducción

Los acantilados costeros son elementos geológico-geomorfológicos que dan lugar a paisajes de alto valor científico, cultural y social en costas de todo el mundo (Emery and Kuhn, 1982; Panizza, 2001; Young, 2018). Estos ambientes naturales presentan una dinámica particularmente activa, en la que destacan los procesos gravitacionales, con el desarrollo de numerosas formas de inestabilidad, que incluyen caídas de rocas y desprendimientos de distinta entidad y desarrollo (Canuti et al., 2009; Westoby et al., 2020; Letortu et al., 2021) como procesos recurrentes (Rosser et al., 2005; Lim et al., 2010; Michoud et al., 2012, Benjamin et al., 2020).

Esta realidad conlleva una elevada susceptibilidad al desarrollo de procesos de ladera, que entronca con la necesidad de elaborar estudios que permitan introducir y evaluar estrategias de gestión adecuadas (Jaboyedoff et al., 2012; Cevasco et al., 2013; Brandolini et al., 2018; Caputo et al., 2018; Federici et al., 2019). Esta aproximación requiere investigaciones de detalle adaptadas a cada entorno, que tengan en cuenta su valor intrínseco, para el desarrollo de acciones sostenibles en el actual contexto de cambio climático global. En este sentido, su estudio a través de modelizaciones tridimensionales probabilísticas (Bourrier et al., 2012; Wang et al., 2014; Asteriou and Tsiambaos, 2018; Tang et al., 2021), con base en informaciones topográficas de detalle (Baum and Godt, 2010; Basher et al., 2015) y el reconocimiento de los condicionantes geológicos y geotécnicos de las inestabilidades (Okura et al., 2000; Dorren et al., 2004; Giacomini et al., 2009; Spadari et al., 2012; Ma et al., 2021), permite contextualizar las caídas de rocas del pasado, analizar las presentes, para elaborar modelos de previsión de futuro.

En el caso de los acantilados costeros que evolucionan hacia playas, vías de tránsito y construcciones a pie de los taludes, las actuaciones a desarrollar requieren un enfoque de protección, conservación y resiliencia (Andrasanu, 2009; Wimbledon and Smith-Meyer, 2012; Brilha, 2018; Accastello et al., 2019; Castelle et al., 2019; Van der Meulen et al., 2022), que determina que la metodología a aplicar adquiera una mayor complejidad (Margottini et al., 2016). La estrategia de gestión de los entornos costeros debe priorizar la intervención mínima frente a acciones constructivas (Yepes et al., 2020), que habitualmente conllevan percepciones negativas (Godschalk et al., 1999; Touili et al., 2014; Gray et al., 2017), minimizando el riesgo mediante actuaciones proporcionales, ajustadas a cada proceso de inestabilidad (Alejano et al., 2007; Hu et al., 2021; Sarro et al., 2021; Bozdag, 2022; Howard and Abbruzzese, 2022). Además, en los últimos años se busca avanzar en dinámicas de investigación con el enfoque de las denominadas Nature-Based Solutions (NBSs), cuya finalidad es trabajar con soluciones adaptadas localmente, que sean eficientes en la utilización de los recursos y holísticas, proporcionando beneficios ambientales, sociales y económicos (Cecchi, 2015; Sarabi et al., 2019; Villegas-Palacio et al., 2020; Kumar et al., 2021; Solheim et al., 2021; Vojinovic et al., 2021).

En este contexto, la presente investigación se ha desarrollado en entornos de alto valor reconocido de los litorales de la Costa Vasca y en Portofino (Costa de Liguria). Inicialmente, se seleccionaron como marco de trabajo la playa de Itzurun (Zumaia) en el Geoparque de la Costa Vasca (capítulo I); la playa de Atxabiribil en Sopelana en el marco de la zona protegida del Flysch de Bizkaia (capítulo II) y las Galerías Punta Begoña en Getxo (capítulo III), en un entorno de notable relevancia cultural y patrimonial. Seguidamente, se desarrollaron dos investigaciones complementarias, una en la playa de Barinatxe de Sopelana (capítulo IV) y otra en las bahías de San Fruttuoso y Paraggi, de la Costa de Liguria, Italia, que ha permitido avanzar en la internacionalización de la investigación (capítulo V).

En el caso de la Costa Vasca, que se considera en los capítulos I, II, III y IV, las investigaciones tienen un carácter complementario, en espacios costeros con procesos de inestabilidad de alta recurrencia y una gestión comprometida debido a su elevado uso. Este litoral incluye un total de 32 Lugares de Interés Geológico (Geosites, LIGs) y dos espacios de especial relevancia geológica y medioambiental: el Geoparque de la Costa Vasca y el Flysch de Bizkaia. En la actualidad, toda la franja costera está protegida en su conjunto como "área de especial protección y mejora ambiental" de acuerdo con el "Plan Territorial Sectorial de Protección y Ordenación del Litoral" del Gobierno Vasco (Decreto 43/2007). De esta forma, las estrategias de gestión a desarrollar deben garantizar los valores naturales y patrimoniales del espacio original, lo que hace necesario un conocimiento de detalle de los procesos dinámicos para su diseño.

En el Parque Natural de Portofino, considerado en el capítulo V, la investigación se ha desarrollado sobre un territorio protegido desde el año 1935, con la creación de la figura de Parque Natural. Desde 1995, la zona es gestionada por la autoridad del propio parque, que definió en el año 1999 el Área Marina Protegida de Portofino, lo que es un valor añadido de cara al desarrollo de gestiones medioambientalmente sostenibles. Por último, en el año 2017 se estableció la figura de Portofino como Parque Nacional, lo que eleva su categoría desde el punto de vista de la protección y conservación de su estado natural.

En todos los casos, los sectores estudiados destacan como espacios naturales con una alta susceptibilidad al desarrollo de caída de rocas, que suponen un riesgo para el gran número de visitantes que acuden a ellos cada año y sus infraestructuras. Es por ello que existe una creciente necesidad de gestionar estos espacios desde un punto de vista medioambientalmente sostenible, utilizando herramientas: efectivas, para resolver el problema; mínimamente invasivas, para preservar el carácter natural del entorno; proporcionales, de acuerdo con los objetivos de estabilidad establecidos; y reversibles, para garantizar la durabilidad del medio.

Los estudios pormenorizados realizados en cada caso permiten diseñar y contrastar aproximaciones de investigación y estrategias de gestión específicas para cada entorno: actuaciones locales constructivas con una alta componente natural (medidas mixtas: capítulos I y V), soluciones de base natural (capítulos II y IV), y acciones de educación, señalización y prevención (capítulos I, II, III, IV y V). En el caso de Punta Begoña, se consideran, en un entorno construido, un seguimiento en continuo para orientar actuaciones proporcionales en un elemento patrimonial singular (medidas constructivas: capítulo III).

En conjunto, la aproximación conceptual, metodológica y de análisis desarrollada en esta tesis permite avanzar en el desarrollo de estrategias de gestión específicas en entornos de alto valor medioambiental, cultural y paisajístico frente a riesgos geológicos, que han sido validadas en cuatro entornos de la Costa Vasca y uno de la Costa de Liguria, y que puede ser ampliada y adaptada a otros entornos, no solo litorales.

1.1 Introduction

Coastal cliffs are geological-geomorphological features that give rise to landscapes of high scientific, cultural and social value on coasts around the world (Emery and Kuhn, 1982; Panizza, 2001; Young, 2018). These natural environments present particularly active dynamics, in which gravitational processes stand out, with the development of numerous forms of instability, including rockfalls and landslides of different entity and development (Canuti et al., 2009; Westoby et al., 2020; Letortu et al., 2021) as recurrent processes (Rosser et al., 2005; Lim et al., 2010; Michoud et al., 2012, Benjamin et al., 2020).

This reality entails a high susceptibility to the development of slope processes, which connects with the need to develop studies that allow the introduction and evaluation of appropriate management strategies (Jaboyedoff et al., 2012; Cevasco et al., 2013; Brandolini et al., 2018; Caputo et al., 2018; Federici et al., 2019). This approach requires detailed investigations adapted to each environment, which take into account their intrinsic value, for the development of sustainable actions in the current context of global climate change. In this sense, its study through probabilistic three-dimensional modeling (Bourrier et al., 2012; Wang et al., 2014; Asteriou and Tsiambaos, 2018; Tang et al., 2021), based on detailed topographic information

(Baum and Godt, 2010; Basher et al., 2015) and the recognition of the geological and geotechnical constraints of instabilities (Okura et al., 2000; Dorren et al., 2004; Giacomini et al., 2009; Spadari et al., 2012; Ma et al., 2021), allows contextualizing past rockfalls, analyzing the present ones, in order to elaborate future forecast models.

In the case of coastal cliffs that evolve into beaches, walkways and constructions at the foot of slopes, the actions to be developed require a protection, conservation and resilience approach (Andrasanu, 2009; Wimbledon and Smith-Meyer, 2012; Brilha, 2018; Accastello et al., 2019; Castelle et al., 2019; Van der Meulen et al., 2022), which determines that the methodology to be applied acquires greater complexity (Margottini et al., 2016). The management strategy for coastal environments should prioritize minimal intervention over constructive actions (Yepes et al., 2020), which usually entail negative perceptions (Godschalk et al., 1999; Touili et al., 2014; Gray et al., 2017), minimizing risk through proportional actions, adjusted to each instability process (Alejano et al., 2007; Hu et al., 2021; Sarro et al., 2021; Bozdag, 2022; Howald and Abbruzzese, 2022). In addition, in recent years, research dynamics have sought to advance with the approach of the so-called Nature-Based Solutions (NBSs), whose purpose is to work with locally adapted solutions that are efficient in the use of resources and holistic, providing environmental, social and economic benefits (Cecchi, 2015; Sarabi et al., 2019; Villegas-Palacio et al., 2020; Kumar et al., 2021; Solheim et al., 2021; Vojinovic et al., 2021).

In this context, the present research has been developed in environments of high-recognized value of the coastlines of the Basque Coast and in Portofino (Ligurian Coast). Initially, the Itzurun beach (Zumaia) in the Basque Coast Geopark (chapter I); the Atxabiribil beach in Sopelana within the protected area of the Flysch of Bizkaia (chapter II) and the Punta Begoña Galleries in Getxo (chapter III), in an environment of remarkable cultural and patrimonial relevance, were selected as a frame of work. Then, two complementary researches were developed, one in the Barinatxe beach of Sopelana (chapter IV) and another one in the bays of San Fruttuoso and Paraggi, in the Ligurian Coast, Italy, which has allowed advancing in the internationalization of the research (chapter V).

In the case of the Basque Coast, which is considered in chapters I, II, III and IV, the research has a complementary character, in coastal areas with highly recurrent instability processes and a compromised management due to its high use. This coastline includes a total of 32 Sites of Geological Interest (Geosites, LIGs) and two areas of special geological and environmental relevance: the Basque Coast Geopark and the Biscay Flysch. At present, the entire coastal strip is protected as a whole as an "area of special protection and environmental improvement" in accordance with the Basque Government's "Sectorial Territorial Plan for the Protection and Management of the Coast" (Decree 43/2007). Thus, the management strategies to be developed must guarantee the natural and heritage values of the original space, which makes detailed knowledge of the dynamic processes necessary for their design.

In the Portofino Natural Park, considered in chapter V, research has been carried out in a protected territory since 1935, with the creation of the Natural Park status. Since 1995, the area has been managed by the park authority itself, which defined in 1999 the Portofino Marine Protected Area, which is an added value for the development of environmentally sustainable management. Finally, in 2017 the figure of Portofino was established as a National Park, which raises its status from the point of view of protection and conservation of its natural state.

In all cases, the sectors studied stand out as natural areas with a high susceptibility to the development of rockfalls, which pose a risk to the large number of visitors who visit them each year and their infrastructures. For this reason, there is a growing need to manage these areas from an environmentally sustainable point of view, using tools that are: effective, to solve the problem; minimally invasive, to preserve the natural character of the environment;

proportional, in accordance with the established stability objectives; and reversible, to guarantee the durability of the environment.

The detailed studies carried out in each case allow us to design and contrast research approaches and specific management strategies for each environment: local constructive actions with a high natural component (mixed measures: chapters I and V), nature-based solutions (chapters II and IV), and education, signaling and prevention actions (chapters I, II, III, IV and V). In the case of Punta Begoña, in a built environment, continuous monitoring is considered to guide proportional actions in a singular heritage element (constructive measures: chapter III).

Overall, the conceptual, methodological and analytical approach developed in this thesis allows to advance in the development of specific management strategies in environments of high environmental, cultural and landscape value against geological hazards, which have been validated in four environments of the Basque Coast and one of the Ligurian Coast, and that can be extended and adapted to other environments, not only coastal.

1.2 Sarrera

Itsaslabarrak elementu geologiko-geomorfologikoak dira, eta balio zientifiko, kultural eta sozial handiko paisaiak sortzen dituzte mundu osoko kostaldeetan (Emery and Kuhn, 1982; Panizza, 2001; Young, 2018). Ingurune natural horiek dinamika bereziki aktiboa dute. Bertan, grabitazio-prozesuak nabarmentzen dira, ezegonkortasun-forma ugari garatuz; besteak beste, arroka-erorketak eta bestelako garrantzia eta garapena duten lur-jausiak (Canuti et al., 2009; Westoby et al., 2020; Letortu et al., 2021) errepikapen handiko prozesu gisa (Rosser et al., 2005; Lim et al 2010).

Errealitate horrek ezegonkortasun-prozesuak garatzeko suszeptibilitate handia dakar, eta horrek lotura du kudeaketa-estrategia egokiak sartu eta ebaluatzeko azterlanak egiteko beharrarekin (Jaboyedoff et al., 2012; Cevasco et al., 2013; Brandolini et al., 2018; Caputo et al., 2018; Federici et al., 2019). Hurbilketa horrek ingurune bakoitzera egokitutako xehetasun-ikerketak eskatzen ditu, haien berezko balioa kontuan hartuko dutenak, egungo klima-aldaketa globalaren testuinguruan ekintza iraunkorrak garatzeko. Alde horretatik, hiru dimentsioko modelizazio probabilistikoen bidez aztertzea (Bourrier et al., 2012; Wang et al., 2014; Asteriou and Tsiambaos, 2018; Tang et al., 2021), informazio topografiko zehatzetan oinarrituta (Baum and Godt, 2010; Basher et al., 2015) eta ezegonkortasunen baldintzatzaile geologiko eta geoteknikoak aintzat hartuta (Okura et al., 2000; Dorren et al., 2004; Giacomini et al., 2009; Spadari et al., 2012; Ma et al., 2021), iraganeko arroken erorketak kokatzeko, gaur-egunekoak aztertzeko eta etorkizuneko gertakizunentzako aurreikuspen-modeloak garatuz.

Hondartzetarantz, igarobideetarantz eta ezponden oinetara doazen itsaslabarren kasuan, egin beharreko jarduerek babes, kontserbazio eta erresilientzia ikuspegia eskatzen dute (Andrasanu, 2009; Wimbledon and Smith-Meyer, 2012; Brilha, 2018; Accastello et al., 2019; Castelle et al., 2019; Van der Meulen et al., 2022), aplikatu beharreko metodologia konplexuagoa izatea zehazten duena (Margottini et al., 2016). Kostaldeko inguruneak kudeatzeko estrategiak lehentasuna eman behar dio eraikuntza minimoko ekintzei (Yepes et al., 2020); beste ekintza konstruktibo horiek, normalean, pertzepzio negatiboak dakartzate eta (Godschalk et al., 1999; Touili et al., 2014; Gray et al., 2017). Edonola, arriskua minimizatu egin behar da, ezegonkortasun-prozesu bakoitzari egokitutako jarduera proportzionalen bidez (Alejano et al., 2007; Hu et al., 2021; Sarro et al., 2021; Bozdag, 2022; Howald and Abbruzzese, 2022). Gainera, azken urteotan ikerketa-dinamiketan aurrera egin nahi da, Naturan Oinarritutako Irtenbideak (NBSs) direlakoen ikuspegiarekin, zeinen helburuak lokalki moldatutako konponbideekin lantzea diren, baliabidetan eraginkorrak eta holistikoak, onurak ingurumenean, sozietatean eta ekonomian eskaintzen dituztenak (Cecchi, 2015; Sarabi et al., 2019; Villegas-Palacio et al., 2020; Kumar et al., 2021; Solheim et al., 2021; Vojinovic et al., 2021).

Testuinguru horretan, ikerketa hau Euskal Kostaldeko eta Portofinoko (Liguriako Kostaldea) balio handiko inguruneetan garatu da. Hasieran, Itzurungo (Zumaia) hondartza aukeratu zen lan-esparru gisa, Euskal Kostaldeko Geoparkean (I. kapitulua); Sopelanako Atxabiribil hondartza, Bizkaiko Flyscharen gune babestuaren esparruan (II. kapitulua), eta Getxoko Punta Begoña galeriak (III. kapitulua), kultura- eta ondare- garrantzi handiko ingurunean. Ondoren, bi ikerketa osagarri egin ziren, bata Sopelako Barinatxeko hondartzan (IV. kapitulua) eta bestea Liguriako Kostako San Fruttuoso eta Paraggi badietan, ikerketaren nazioartekotzean aurrera egiteko aukera eman duena (V. kapitulua).

Euskal Kostaren kasuan I., II., III. eta IV. kapituluetan aipatzen da, eta ikerketa osagarriak dira, errekurrentzia handiko ezegonkortasun-prozesuak eta kudeaketa konprometitua dituzten kostaldeko eremuetan, asko erabiltzen direlako. Itsasertz horretan, interes geologikoko 32 leku (geositeak, GILak) eta garrantzi geologiko eta ingurumeneko bereziko bi gune daude: Euskal Kostaldeko Geoparkea eta Bizkaiko Flyscha. Gaur egun, itsasertzeko zerrenda osoa “ingurumena babesteko eta hobetzeko eremu berezi” gisa babestuta dago, Eusko Jaurlaritzaren “Itsasertza Babesteko eta Antolatzeko Lurralde Plan Sektorialaren” arabera (43/2007 Dekretua). Horrela, garatu beharreko kudeaketa-estrategiek jatorrizko espazioaren natura- eta ondare-balioak bermatu behar dituzte, eta, horretarako, beharrezkoa da prozesu dinamikoak xehetasunez ezagutzea, ahalik eta hoberen diseinatzeko.

Portofinoko Parke Naturalean (V. kapituluan aztertzen da), 1935az geroztik Parke Naturala den babestutako lurralde batean egin da ikerketa. 1995az geroztik, parkeko bertako agintaritzak kudeatzen du eremua; 1999an Portofinoko Itsas Eremu Babestua definitu zuen, eta hori balio erantsia da ingurumenaren aldetik iraunkorrak diren kudeaketak garatzeko. Azkenik, 2017an

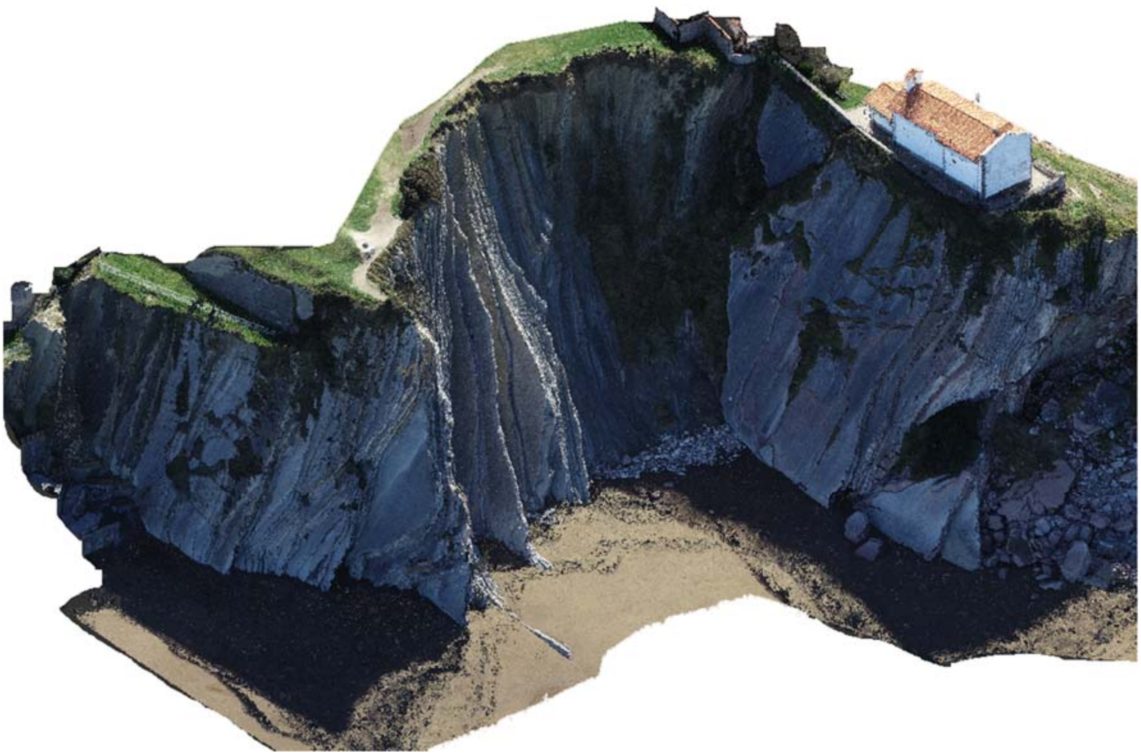
Portofinoren irudia ezarri zen Parke Nazional gisa, eta horrek bere kategoria handitu du bere egoera naturalaren babes eta kontserbazioaren ikuspuntutik.

Kasu guztietan, aztertutako sektoreak arrokak erortzeko joera handia duten naturgune gisa nabarmentzen dira, eta horrek arriskuan jartzen ditu urtero haietara joaten diren bisitariak eta haien azpiegiturak. Hori dela eta, gero eta beharrezkoagoa da eremu horiek ingurumenaren aldetik iraunkorra den ikuspegitik kudeatzea, tresna eraginkorrak erabiliz arazoa konpontzeko; gutxienezko inbasibotasuna daukatenak, ingurunearen izaera naturala babesteko; proportzionalak, ezarritako egonkortasun-helburuen arabera; eta itzulgarriak, ingurunearen iraunkortasuna bermatzeko.

Kasu bakoitzean egindako azterketa espezifikoek aukera ematen dute ingurune bakoitzerako ikerketa-hurbilketak eta kudeaketa-estrategia espezifikoak diseinatzeko eta kontrastatzeko: osagai natural handiko tokiko jarduerak (neurri mistoak: I. eta V. kapituluak), oinarri naturaleko irtenbideak (II. eta IV. kapituluak), eta hezkuntza-, seinaleztapen- eta prebentzio-ekintzak (I., II., III., IV. eta V. kapituluak). Punta Begoñaren kasuan, eraikitako inguru batean etengabeko jarraipena egiten da, ondare elementu berezi batean jarduera proportzionalak bideratzeko (eraikuntza neurriak: III. kapitulua).

Oro har, tesi honetan garatutako kontzeptu-, metodologia- eta analisi-hurbilketak aukera ematen du ingurumen-, kultura- eta paisaia-balio handiko inguruneetan kudeaketa-estrategia espezifikoak garatzeko, arrisku geologikoen aurrean. Estrategia horiek Euskal Kostaldeko lau ingurunetan eta Liguriako Kostako batean balioztatu dira, eta beste ingurune batzuetara zabal eta egoki daitezke, ez itsasertzera bakarrik.

2. Contexto e interés global de la investigación



Nube de puntos del entorno de la ermita de San Telmo (Zumaia)

2. Contexto e interés global de la investigación

Las costas rocosas representan alrededor del 75-80% de los litorales del mundo (Emery and Khun, 1982; Sunamura, 1992), dando lugar a paisajes únicos de alto valor científico, cultural y social (Panizza, 2001; Kubalíková, 2013; Kirchner and Kubalíková, 2013; Kirchner and Kubalíková, 2015; Young, 2018), entre los que destacan los acantilados que se elevan sobre las plataformas intermareales, sobre playas o directamente sobre el mar (Trenhaile, 2010; Sunamura, 2015). Se trata de entornos particularmente activos, afectados por procesos marinos y ambientales, en los que la geometría costera, la litología de los materiales y sus características estructurales, actúan como significativos factores condicionantes de su evolución (Sunamura, 1992; Duperret et al., 2004; Hampton and Griggs, 2004).

El interés por su investigación ha aumentado principalmente en los últimos años (Naylor et al., 2010), a medida que su ocupación y uso han generado un problema de creciente magnitud (Moore and Griggs, 2002) entre la actividad humana y los procesos de inestabilidad.

En este contexto, en las últimas décadas, un elevado número de trabajos de investigación han avanzado en el estudio del desarrollo de inestabilidades y la medición del retroceso de la línea de costa (Epifanio et al., 2013; Prémaillon et al., 2018; Domínguez-Cuesta et al., 2020; Cuervas-Mons et al., 2021; Domínguez-Cuesta et al., 2022) desde un punto de vista eminentemente evolutivo.

Otro enfoque prioritario se centra en el análisis de los procesos de caída de rocas desde los acantilados rocosos (Gibb, 1978; Rosser et al., 2007; Hapke et al., 2009; Whadcoat et al., 2017), en vistas a la gestión de riesgos. En este sentido, estos procesos suelen ser extremadamente rápidos (Corominas et al., 2017), y la capacidad de reacción para evitar sus daños es limitada (Volkwein et al., 2011), por lo que la actuación mediante medidas preventivas se muestra como particularmente recomendable. En este sentido, clásicamente se ha trabajado con intervenciones de regulación y planificación de usos del suelo y medidas estructurales como muros, cunetas de recogida y barreras, con el fin de aumentar el nivel de protección (Holub and Hübl, 2008; Moos et al., 2018; Accastello et al., 2019). Los aspectos negativos de estas medidas, como los elevados costes de construcción y mantenimiento que conllevan y el impacto ambiental y estético que suponen (Godschalk et al., 1999; Touili et al., 2014; Gray et al., 2017), ha llevado a una creciente búsqueda de medidas no estructurales menos invasivas (Li and Eddleman, 2002; Cruz, 2007; Lacambra et al., 2008), combinadas con estrategias de prevención, alerta y educación basadas en análisis detallados del terreno (Baum and Godt, 2010; Basher et al., 2015).

El interés de estos trabajos ha hecho que la producción científica en temas relacionados con las caídas de rocas haya experimentado una evolución exponencialmente creciente en el tiempo. Así, mientras entre los años 1975 y 2001 se registran sobre una centena de publicaciones, en el periodo de 2002 a 2016 se alcanzan prácticamente las 500 publicaciones, con una media de 33.13 documentos al año, y la tendencia se consolida, como un punto fundamental del estudio sobre riesgos geológicos, con más de 200 publicaciones entre 2017 y 2019 (Briones-Bitar et al., 2020). La curva de evolución de las publicaciones presenta un ascenso evidente (Figura 1), que se ve favorecido por el desarrollo de nuevas tecnologías de adquisición y análisis de la información (Sarro et al., 2018; Zabota and Kobal, 2020; Akin et al., 2021), la consideración de nuevos enfoques de protección más sostenibles (Masuya et al., 2009; Chen et al., 2013) y la valoración de la influencia del cambio climático en el proceso (Bodin et al., 2015; Gallach et al., 2020).

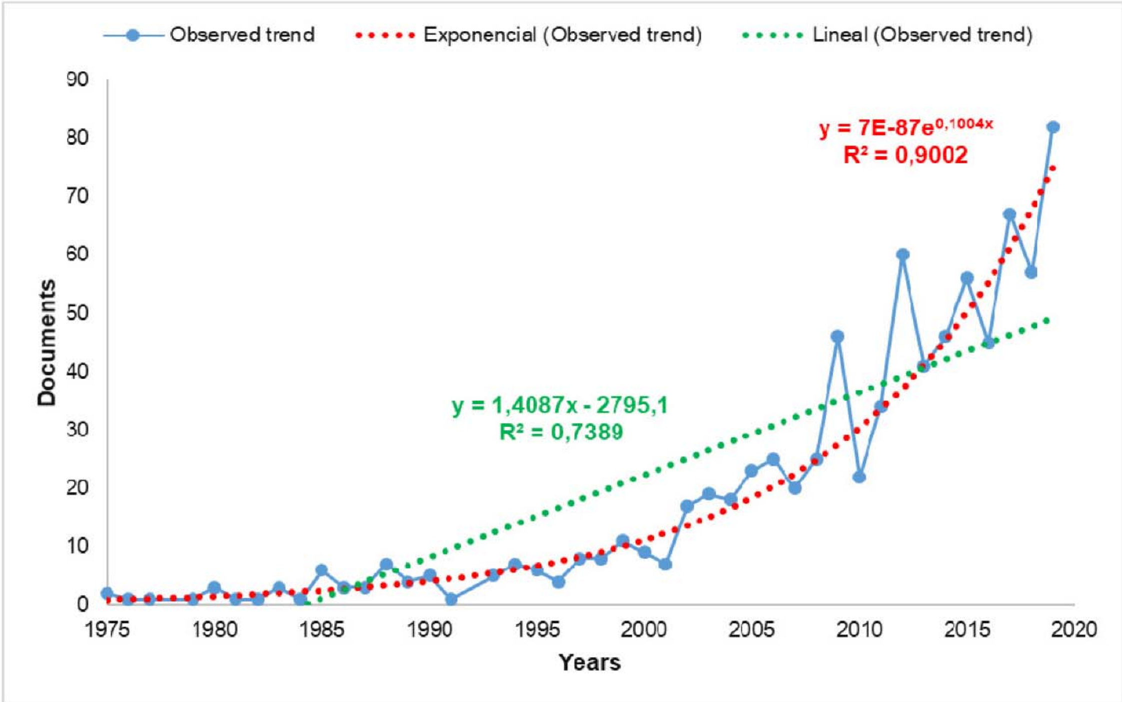


Figura 1. Producción científica de artículos de caída de rocas. Ajustes de las líneas de tendencia lineales y exponenciales para el número de publicaciones (Briones-Bitar et al., 2020)

En cuanto a las estrategias de obtención de imágenes, existe una amplia gama de técnicas de trabajo complementarias que permiten documentar geométrica y visualmente la realidad física con gran detalle, rapidez y precisión (Margottini et al. 2015; Themistocleous and Danezis, 2019); incluyendo el uso del láser escáner terrestre (TLS) o aerotransportado (ALS) para obtener imágenes LiDAR, la interferometría satelital (InSAR) y de radar terrestre (GB-InSAR), o imágenes fotogramétricas obtenidas mediante vehículo aéreo tripulado, no tripulado (VANT) y sobre el terreno (Colomina and Molina 2014; Tang et al. 2016).

El alcance, precisión-resolución y capacidades de estos equipos en continuo desarrollo, permiten una caracterización y seguimiento del terreno a distintas escalas (Collins and Sitar 2008; Jaboyedoff et al., 2012; Abellán et al., 2014), resultando particularmente útiles en entornos inestables (Williams et al., 2018; Gilham et al., 2019; Guerin et al., 2020).

A partir de esta información se obtienen imágenes detalladas del terreno, que una vez georreferenciadas pueden ser utilizadas para obtener, a partir de las nubes de puntos obtenidas, modelos tridimensionales del terreno en formato ráster que pueden ser combinados con otras informaciones de distinta naturaleza mediante Sistemas de Información Geográfica (SIG) (Adam et al., 2002; Bruyninx et al., 2019), y son la base para el desarrollo de los modelos de simulación.

En el caso de caída de rocas, las modelizaciones permiten el análisis de trayectorias a escala bidimensional (Azzoni et al., 1995; Chen et al., 2013; Keskin, 2013) y tridimensional, incluyendo, en este caso, la evaluación de energía, evolución lateral y alcance de los desprendimientos (Li and Lan, 2015; Margottini et al., 2015; Sarro et al., 2018; Akin et al., 2021), tanto a escala regional (Antoniou, 2013; Fanos and Pradhan, 2016) como local (Gigli et al., 2014; Sarro et al., 2018; Fanos and Pradhan, 2019; Sala et al., 2019).

Estos seguimientos pueden ser complementados con redes de control geotécnico ubicadas in situ, que permiten, en el caso de movimientos extremadamente lentos (Greif et al., 2006), seguimientos en continuo de alta precisión. La principal limitación de estos dispositivos es su establecido alcance espacial (Zhu et al. 2017; Themistocleous et al. 2018), mientras que su principal ventaja es que permiten el registro directo y continuo del desplazamiento en escalas de corto y largo plazo.

Esta información de detalle es la base para el desarrollo de estrategias de gestión de espacios de alto valor natural, paisajístico y social, más sostenibles y proporcionales a sus características específicas. En este sentido, en los últimos tiempos, han aumentado los esfuerzos para abordar los desafíos ambientales, sociales y económicos a través de lo que se conoce como soluciones basadas en la naturaleza (NBSs). Aunque existe una amplia gama de definiciones de las NBSs (Sarabi et al., 2019; Solheim et al., 2021), la Comisión Europea (Cecchi, 2015) las identifica como: "Soluciones que se inspiran y apoyan en la naturaleza, que son rentables, proporcionan simultáneamente beneficios ambientales, sociales y económicos y ayudan a crear resiliencia. Dichas soluciones aportan más naturaleza, características y procesos naturales a las ciudades, los paisajes terrestres y marinos, a través de intervenciones adaptadas localmente, eficientes en cuanto a recursos y sistémicas".

2.1 Context and overall research interest

Rocky coasts represent about 75-80% of the world's shorelines (Emery and Khun, 1982; Sunamura, 1992), giving rise to unique landscapes of high scientific, cultural and social value (Panizza, 2001; Kubalíková, 2013; Kirchner and Kubalíková, 2013; Kirchner and Kubalíková, 2015; Young, 2018), among which cliffs rising over wave-cut platforms, over beaches or directly over the sea stand out (Trenhaile, 2010; Sunamura, 2015). These are particularly active environments, affected by marine and environmental processes, in which the coastal geometry, the lithology of the materials and their structural characteristics, act as significant conditioning factors in their evolution (Sunamura, 1992; Duperret et al., 2004; Hampton and Griggs, 2004).

Interest in their research has mainly increased in recent years (Naylor et al., 2010), as their occupation and use have generated a problem of increasing magnitude (Moore and Griggs, 2002) between human activity and instability processes.

In this context, in the last decades, a high number of research works have advanced in the study of the development of instabilities and the measurement of shoreline retreat (Epifanio et al., 2013; Prémaillon et al., 2018; Domínguez-Cuesta et al., 2020; Cuervas-Mons et al., 2021; Domínguez-Cuesta et al., 2022) from an eminently evolutionary point of view.

Another priority approach focuses on the analysis of rockfall processes from rocky cliffs (Gibb, 1978; Rosser et al., 2007; Hapke et al., 2009; Whadcoat et al., 2017), in view of risk management. In this sense, these processes are usually extremely fast (Corominas et al., 2017), and the reaction capacity to avoid their damage is limited (Volkwein et al., 2011), so that action through preventive measures is shown to be particularly advisable. In this sense, classically, work has been done with regulatory and land use planning interventions and structural measures such as walls, collection ditches and barriers, in order to increase the level of protection (Holub and Hübl, 2008; Moos et al., 2018; Accastello et al., 2019). The negative aspects of these measures, such as the high construction and maintenance costs involved and the environmental and aesthetic impact they entail (Godschalk et al., 1999; Touili et al., 2014; Gray et al., 2017), led to a growing search for less invasive non-structural measures (Li and Eddleman, 2002; Cruz, 2007; Lacambra et al., 2008), combined with prevention, warning and education strategies based on detailed field analysis (Baum and Godt, 2010; Basher et al., 2015).

The interest of these works has led to an exponentially increasing evolution of the scientific production in topics related to rockfalls over time. Thus, while between the years 1975 and 2001 around a hundred publications are recorded, in the period from 2002 to 2016 almost 500 publications are reached, with an average of 33.13 papers per year, and the trend is consolidated, as a fundamental point of the study on geological hazards, with more than 200 publications between 2017 and 2019 (Briones-Bitar et al., 2020). The evolution curve of publications shows an evident ascent (Figure 1), which is favored by the development of new information acquisition and analysis technologies (Sarro et al., 2018; Zabota and Kobal, 2020; Akin et al., 2021), the consideration of new and more sustainable protection approaches (Masuya et al., 2009; Chen et al., 2013) and the assessment of the influence of climate change in the process (Bodin et al., 2015; Gallach et al., 2020).

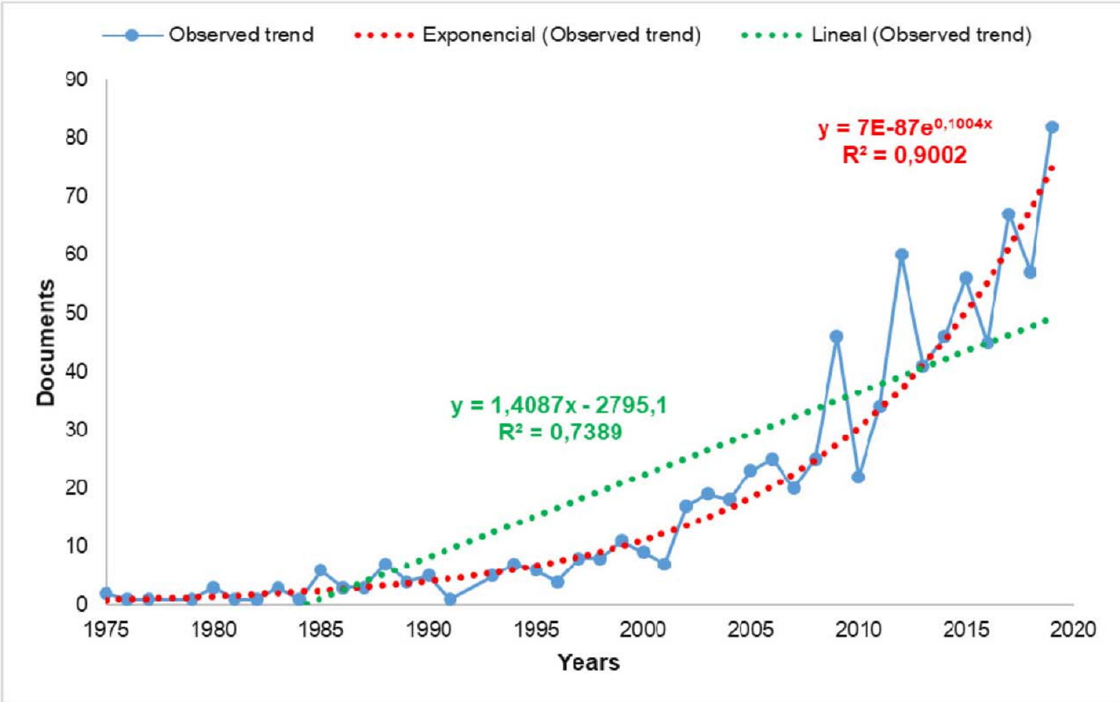


Figure 1. Scientific production of rockfall articles. Linear and exponential trend line fits for the number of publications (Briones-Bitar et al., 2020).

In terms of imaging strategies, there is a wide range of complementary working techniques that allow geometrically and visually documenting physical reality with great detail, speed and accuracy (Margottini et al. 2015; Themistocleous and Danezis, 2019); including the use of terrestrial (TLS) or airborne (ALS) laser scanning for LiDAR imaging, satellite (InSAR) and ground-based radar (GB-InSAR) interferometry, and photogrammetric imagery obtained by manned aerial vehicle, unmanned aerial vehicle (UAV) and on the ground (Colomina and Molina 2014; Tang et al. 2016).

The range, accuracy-resolution and capabilities of this equipment in continuous development, allow terrain characterization and monitoring at different scales (Collins and Sitar 2008; Jaboyedoff et al., 2012; Abellán et al., 2014), proving particularly useful in unstable environments (Williams et al., 2018; Gilham et al., 2019; Guerin et al., 2020).

From this information, detailed images of the terrain are obtained, which once georeferenced can be used to acquire, from the point clouds obtained, three-dimensional terrain models in raster format that can be combined with other information of different nature through Geographic Information Systems (GIS) (Adam et al., 2002; Bruyninx et al., 2019), and are the basis for the development of simulation models.

In the case of rockfall, modeling allows the analysis of trajectories at two-dimensional (Azzoni et al., 1995; Chen et al., 2013; Keskin, 2013) and three-dimensional scales, including, in this case, the assessment of energy, lateral evolution and runout of detachments (Li and Lan, 2015; Margottini et al., 2015; Sarro et al., 2018; Akin et al., 2021), both at regional (Antoniou, 2013; Fanos and Pradhan, 2016) and local (Gigli et al., 2014; Sarro et al., 2018; Fanos and Pradhan, 2019; Sala et al., 2019) scales.

This detailed information is the basis for the development of management strategies for areas of high natural, landscape and social value that are more sustainable and proportional to their specific characteristics. In this regard, in recent times, efforts to address environmental, social and economic challenges through what are known as nature-based solutions (NBSs) have increased. Although there is a wide range of definitions of NBSs (Sarabi et al., 2019; Solheim et al., 2021), the European Commission (Cecchi, 2015) identifies them as: "Solutions that are inspired and supported by nature, that are cost-effective, provide simultaneous environmental, social and economic benefits and help build resilience. Such solutions bring more nature, natural features and processes to cities, landscapes and seascapes through locally adapted, resource-efficient and systemic interventions."

2.2 Testuingurua eta ikerketaren interes globala

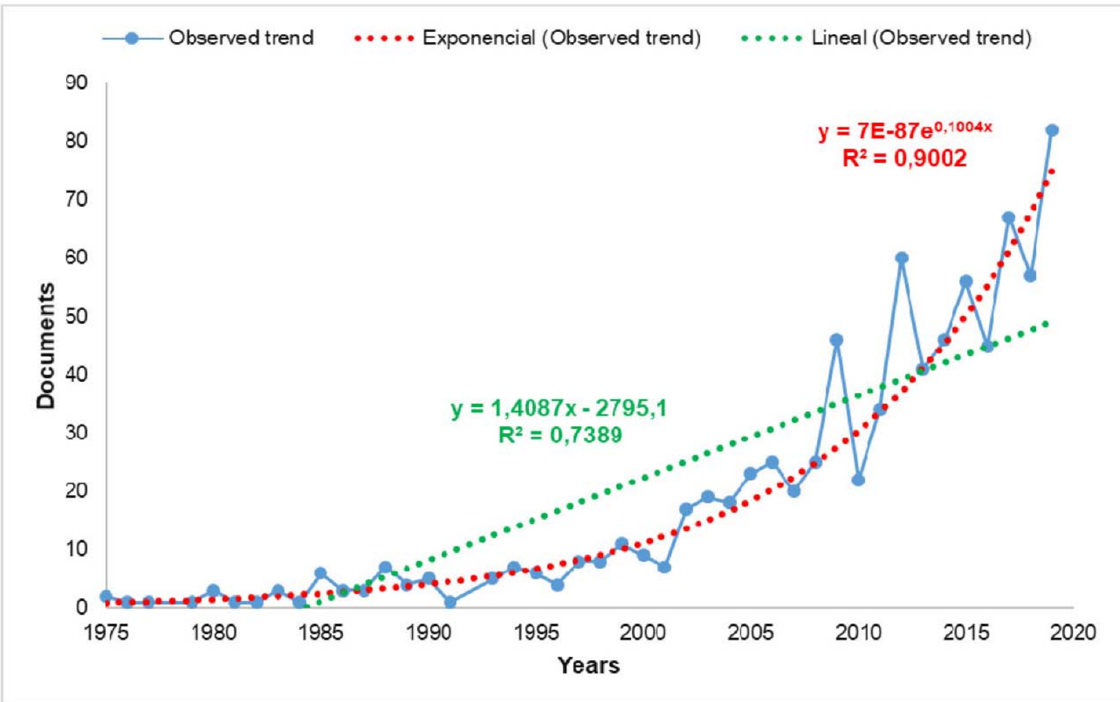
Kostalde arrokatsuek munduko itsasbazterren %75-80 inguru ordezkatzen dute (Emery and Khun, 1982; Sunamura, 1992), eta balio zientifiko, kultural eta sozial handiko paisaia paregabeak sortzen dituzte (Panizza, 2001; Kubaliková, 2013; Kirchner and Kubaliková, 2015; Young, 2018), horien artean, marearteko plataformen gainean, hondartzen gainean edo zuzenean itsasoaren gainean dauden itsaslabarrak nabarmentzen dira (Trenhaile, 2010; Sunamura, 2015). Ingurune bereziki aktiboak dira, itsas- eta ingurumen-prozesuen eragina dutenak. Kostaldeko geometriak, materialen litologiak eta haien egitura-ezaugarriek baldintzatzen dute haien bilakaera (Sunamura, 1992; Duperret et al., 2004; Hampton y Griggs, 2004).

Haren ikerketarekiko interesa handitu egin da batez ere azken urteotan (Naylor et al., 2010), gaur eguneko okupazioak eta erabilerak giza jardueraren eta ezegonkortasun-prozesuen arteko arazo gero eta handiagoa sortu ahala (Moore and Griggs, 2002).

Testuinguru horretan, azken hamarkadetan, ikerketa-lan ugarik egin dute aurrera ezegonkortasunen garapenean eta kosta-lerroaren atzerapena neurtzean (Epifanio et al., 2013; Prémaillon et al., 2018; Domínguez-Cuesta et al., 2020; Cuervas-Mons et al., 2021; Domínguez-Cuesta et al., 2022), ikuspegi erabat ebolutibotik.

Lehentasunezko beste ikuspegi bat labar harritsuetatik arrokak erortzeko prozesuak aztertzea da (Gibb, 1978; Rosser et al., 2007; Hapke et al., 2009; Whadcoat et al., 2017), arriskuen kudeaketari begira. Alde horretatik, prozesu horiek oso azkarrak izan ohi dira (Corominas et al., 2017), eta kalteak saihesteko erreakzio-gaitasuna mugatua da (Volkwein et al., 2011); beraz, prebentzio-neurrien bidezko jarduera bereziki gomendagarria da. Alde horretatik, lurzoruaren erabilerak arautzeko eta planifikatzeko esku-hartzeekin eta egiturazko neurriekin egin da lan, hala nola hormekin, bilketako arekekin eta hesiekin, babes-maila handitzeko (Holub eta Hübl, 2008; Moos et al., 2018; Accastello et al., 2019). Neurri horien alderdi negatiboak, besteak beste, eraikuntza- eta mantentze-kostu handiak eta horiek ingurumenean eta estetikan duten eragina dira (Godschalk et al., 1999; Touili et al., 2014; Gray et al., 2017). Horren ondorioz, egiturazko neurri ez hain inbaditzaileak bilatu dira (Li y Eddleman, 2002; Cruz, 2007; Lacambra et al., 2008), prebentzio-, alerta- eta hezkuntza-estrategiekin konbinatuta, lurraren azterketa zehatzetan oinarrituta (Baum eta Godt, 2010; Basher et al., 2015).

Lan horien interesaren ondorioz, arroken erorketekin lotutako ekoizpen zientifikoak bilakaera esponentzialki gorakorra izan du denboran. Hala, 1975 eta 2001 urteen artean ehun argitalpen inguru izan ziren, eta 2002 eta 2016 artean, berriz, ia 500 argitalpen izan ziren, batez beste 33,13 dokumentu urtean, eta joera finkatu egin da, arrisku geologikoei buruzko azterketaren funtsezko puntu gisa, 200 argitalpen baino gehiago izan baitira 2017 eta 2019 artean (Briones-Bitar et al., 2020). Argitalpenen bilakaera-kurbak gorakada nabarmena izan du (1. irudia), informazioa eskuratzeko eta aztertzeko teknologia berrien garapenak lagunduta (Sarro et al., 2018; Zabota and Kobal, 2020; Akin et al., 2021), babes-ikuspegi iraunkorragoak hartzean (Masuya et al., 2009; Chen et al., 2013) eta klima-aldaketak prozesuan duen eragina baloratzean (Bodin et al., 2015; Gallach et al., 2020).



1Irudia. Arrokak erortzeko gaien produkzio zientifikoa. Joera-lerro linealen eta esponentzialen doikuntzak argitalpen-kopuruarentzat (Briones-Bitar et al., 2020).

Irudiak lortzeko estrategiei dagokienez, lan-teknika osagarri ugari daude, errealitate fisikoa doitasun, azkartasun eta zehaztasun handiz geometrikoki dokumentatzeko (Margottini et al. 2015; Themistocleous y Danezis, 2019); besteak beste, lurreko eskaner-laserra (TLS) edo aerotransportatua (ALS) erabiltzea LiDAR irudiak lortzeko, satelite bidezko interferometria (InSAR) eta lurreko radarra (GB-InSAR), eta tripulatu edo tripulatu gabeko aireko ibilgailuen bidez lortutako irudi fotogrametrikoak (Colomina and Molina 2014; Tang et al., 2016).

Ekipamendu horien irismenari, ebazpenari eta gaitasunei esker, lurzoruaren karakterizazioa eta jarraipena egin daiteke eskala desberdinetan (Collins and Sitar 2008; Jaboyedoff et al., 2012; Abellán et al., 2014), eta bereziki erabilgarriak dira ingurune ezegonkorretan (Williams et al., 2018; Gilet al., 2019; Guerin et al., 2020).

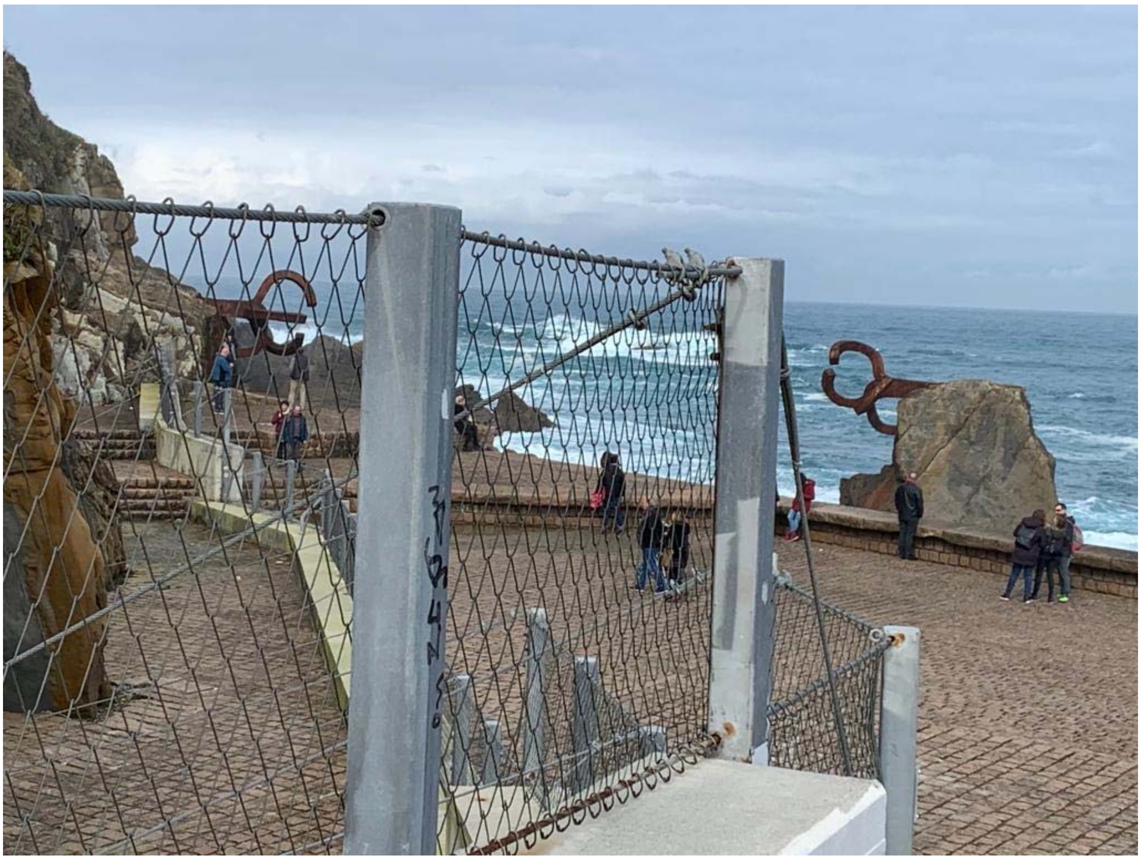
Informazio horretatik abiatuta, lurzoruaren irudi zehatzak lortzen dira. Irudi horiek, geoerreferentziatu ondoren, lurzoruaren hiru dimentsioko ereduak lortzeko erabil daitezke, lortutako puntu-hodeietatik abiatuta, raster formatuan. Eredu horiek Informazio Geografikoko Sistemen (IGS) bidez (Adam et al., 2002; Bruyninx et al., 2019), garapenerako ereduak dira.

Arrokak eroriz gero, modelizazioei esker, bi dimentsioko ibilbideak (Azzoni et al., 1995; Chen et al., 2013; Keskin, 2013) eta hiru dimentsioko ibilbideak azter daitezke, eta, kasu horretan, energia, alboko bilakaera eta harri-jausien irismena ebaluatu (Li and Lan, 2015; Margottini et al., 2015; Sarro, 2015), bai eskualde-mailan (Antoniou, 2013; Fanos and Pradhan, 2016), bai tokiko mailan (Gigli et al., 2014; Sarro et al., 2018; Fanos and Pradhan, 2019; Sala et al., 2019).

Jarraipen horiek in situ kokatutako kontrol geoteknikoko sareekin osa daitezke. Sare horiek, mugimendu oso motelen kasuan (Greif et al., 2006), doitasun handiko segimendu jarraituak egiteko aukera ematen dute. Gailu horien muga nagusia irismen espazial mugatua dutela da (Zhu et al. 2017; Themistocleous et al. 2018). Abantaila nagusia, berriz, desplazamendua zuzenean eta etengabe erregistratzea ahalbidetzen dutela, epe labur eta luzeko eskaletan.

Informazio xehe hori natura, paisaia eta gizarte aldetik balio handia duten espazioak kudeatzeko estrategien garapenerako oinarria da, iraunkorragoak eta beren ezaugarri berariazkoekin proportzionalak direnak. Alde horretatik, azkenaldian, ahalegin handiagoa egin da ingurumen-, gizarte- eta ekonomia-erronkei naturan oinarritutako irtenbideak (NBS) direlakoen bidez aurre egiteko. NBSen definizio-sorta zabala dagoen arren (Sarabi et al., 2019; Solheim et al., 2021), Europako Batzordeak (Cecchi, 2015) honela identifikatzen ditu: "Naturan inspiratzen diren eta laguntzen duten irtenbideak, errentagarriak direnak, aldi berean ingurumen-, gizarte- eta ekonomia-onurak ekartzen dituztenak eta erresilientzia sortzen laguntzen dutenak. Konponbide horiek natura, ezaugarri eta prozesu natural gehiago ematen diete hiriei, lurreko eta itsasoko paisaiei, tokian tokiko esku-hartze eraginkorren bidez, baliabideei eta sistemikoei dagokienez".

3. Hipótesis y objetivos generales y específicos



Actuaciones recientes en la plaza Peña-Gantxegi de Donostia-San Sebastián

3. Hipótesis y objetivos generales y específicos

El desarrollo científico y tecnológico actual permite realizar actuaciones de distinta naturaleza en el territorio con un amplio abanico de enfoques, que van desde contundentes intervenciones constructivas a planes de gestión sostenible que buscan ser mínimamente invasivos con medidas locales de bajo impacto. En el caso de riesgos por caída de rocas, la aproximación constructiva busca disminuir el nivel de riesgo, sin profundizar en los aspectos medioambientales de los sistemas socio-ecológicos sobre los que se actúa (Accastello et al., 2019). Estas medidas, aunque pueden resultar necesarias, constituyen una fuente de perturbación en su entorno (O'Farrell and Anderson, 2010; Rimbock et al., 2014), como las desarrolladas en el Peine del Viento en Donostia-San Sebastián.

En el otro extremo, las actuaciones basadas en propuestas medioambientalmente amistosas (friendly) buscan preservar el carácter original del lugar, mediante el uso de aproximaciones que impliquen su protección y desarrollo (Margottini et al., 2016), con medidas proporcionales a los objetivos de seguridad establecidos y el menor daño posible a sus valores naturales y culturales.

Esta aproximación, entronca con las directrices de las Nature-Based Solutions (NBSs), que buscan garantizar la conservación de los espacios naturales y beneficiar a la sociedad, mitigando los riesgos y aumentando la resiliencia (Villegas-Palacio et al., 2020; Kumar et al., 2021; Vojinovic et al., 2021; Wu et al., 2021).

La aplicación de este enfoque en el estudio de los procesos de inestabilidad hace imprescindible el desarrollo de estrategias para la obtención de informaciones detalladas del territorio (Abellán et al., 2010; Pham et al., 2016; Fanos and Pradhan, 2019), que permitan desarrollar análisis de simulación y modelizaciones precisas (Dorren, 2003; Lan et al., 2007; Stoffel et al., 2010; Keskin, 2013; Ansari et al., 2018), con las que contrastar propuestas de actuación adaptadas a las dinámicas de los entornos de estudio.

De esta forma, la presente tesis aborda, a partir de aproximaciones metodológicas específicas, la gestión del riesgo de caída de rocas, que es uno de los procesos más recurrentes en ambientes costeros (Rosser et al., 2005; Michoud et al., 2012), en cuatro entornos del litoral vasco y uno de Liguria, a partir de su estudio de detalle.

El objetivo principal de esta tesis es establecer un marco conceptual para el desarrollo de estrategias integradas de gestión de riesgos medioambiental y socialmente sostenibles, en entornos litorales con acantilados costeros. Estas aproximaciones buscan avanzar en la incorporación de medidas basadas en la naturaleza o de mínimo impacto, y documentar su eficiencia solas o combinadas, en un plan de gestión conjunto del territorio y del paisaje.

En este marco general, se pueden diferenciar como objetivos específicos:

OBJETIVO 1. Avanzar en la caracterización, desde un punto de vista geomecánico, de los materiales rocosos que constituyen los acantilados y reconocer la tipología de elementos inestables en función de la orientación de los acantilados respecto al macizo rocoso y sus discontinuidades.

En este sentido, el análisis geomecánico es una herramienta adecuada para comprender los mecanismos subyacentes que impulsan la inestabilidad, al existir una clara relación entre la disposición de discontinuidades, su orientación, espaciado y persistencia, y la tipología de roturas (Cooke et al, 2006; Corominas et al., 2017; McGinnis et al., 2017).

Este objetivo se aborda en los capítulos I, II, III, IV y V, puesto que resulta el primer acercamiento a los materiales geológicos en los entornos de trabajo.

OBJETIVO 2. Desarrollar y generar la información topográfica de detalle (MDT, nubes de puntos, ortofotos) que sirva de base para el desarrollo de modelizaciones tridimensionales, mediante LiDAR satelital, Láser Escáner Terrestre y fotogrametría mediante Vehículos Aéreos No Tripulados (VANT o "dron") según el caso y atendiendo a las características y limitaciones de cada zona de estudio.

Así, la investigación en Italia se ha realizado mediante técnicas LiDAR satelitales (capítulo V), mientras que el resto de investigaciones se han desarrollado mediante Láser Escáner Terrestre (capítulos II, III, IV) y VANT (capítulo I) sobre el terreno.

OBJETIVO 3. Seguimiento de desprendimientos, magnitud y frecuencia. Identificación, caracterización y análisis de áreas fuente de caída de rocas, tipología de rotura, trayectorias, características dimensionales y alcance de los bloques desprendidos.

Este objetivo se ha abordado en los capítulos I, II, IV y V, en los que la evolución de los acantilados se desarrolla, en gran medida, mediante desprendimientos continuos que pueden ser identificados y contextualizados según su escala espacial y temporal.

OBJETIVO 4. Avanzar en la utilización de redes de control geotécnico dispuestas in situ para realizar seguimientos en continuo de gran precisión.

Esta metodología se ha implementado específicamente en el capítulo III, en el que se ha realizado una evaluación de movimientos estructurales extremadamente lentos (Greif et al., 2006) a largo plazo (long-term) mediante análisis espectrales. Estas técnicas podrán ser extrapolables tanto a otros entornos culturales como naturales.

OBJETIVO 5. Desarrollar y adaptar modelos de simulación de trayectoria de caídas, que permitan reconocer, como parámetros básicos, su alcance, altura y energía a lo largo de las vertientes, incluyendo la dispersión lateral de las trayectorias. Esta aproximación permite avanzar en la valoración y validación de los parámetros característicos que condicionan la evolución de los fragmentos rocosos en distintos materiales y contextos.

Este objetivo, que constituye uno de los puntos principales de la investigación realizada, se ha desarrollado en los capítulos I, II, IV y V.

OBJETIVO 6. Integrar el conjunto de información previa en zonificaciones precisas de susceptibilidad al alcance, energía cinética, altura y peligrosidad de los desprendimientos, y valorar soluciones de protección y gestión adaptadas a cada entorno, en función de sus valores naturales y paisajísticos.

Tabla 1. Objetivos de la tesis doctoral

OBJETIVO	*Capítulo I*	*Capítulo II*	*Capítulo III*	*Capítulo IV*	*Capítulo V*
OBJETIVO 1 Avanzar en la caracterización geomecánica y tipología de inestabilidades	📍	📍	📍	📍	📍
OBJETIVO 2 Desarrollar y generar información topográfica de detalle (LiDAR, MDT, nubes de puntos...)	📍	📍	📍	📍	📍
OBJETIVO 3 Seguimiento de desprendimientos, magnitud y frecuencia: áreas fuente, trayectorias, características dimensionales y alcance de bloques	📍	📍		📍	📍
OBJETIVO 4 Avanzar en la utilización de redes geotécnicas in situ para realizar seguimientos en continuo de movimientos extremadamente lentos			📍		
OBJETIVO 5 Desarrollar y adaptar modelos tridimensionales de trayectoria de caída de rocas	📍	📍		📍	📍
OBJETIVO 6 Integrar la información generada para la elaboración de mapas de susceptibilidad y peligrosidad, y valorar las actuaciones de protección y gestión	📍	📍		📍	📍

Este apartado se ha realizado en los capítulos I, II, IV y V. Aunque el estudio de actuaciones singulares para elaborar planes de gestión se ha desarrollado de acuerdo con las particularidades de cada entorno, la aproximación desarrollada en su conjunto puede ser adaptada y extrapolada a otros espacios con problemáticas análogas, tanto litorales como de interior, priorizando la consideración de medidas no estructurales, combinadas con estrategias de prevención, alerta y educación.

3.1. General and specific hypotheses and objectives

Current scientific and technological development allows actions of different nature to be carried out in the territory with a wide range of approaches, ranging from forceful constructive interventions to sustainable management plans that seek to be minimally invasive with low-impact local measures. In the case of rockfall risks, the constructive approach seeks to decrease the level of risk, without delving into the environmental aspects of the socio-ecological systems on which action is taken (Accastello et al., 2019). These measures, although they may be necessary, constitute a source of disturbance in their environment (O'Farrell and Anderson, 2010; Rimbock et al., 2014), such as those developed at the Comb of the Wind in Donostia-San Sebastián.

At the other extreme, actions based on environmentally friendly proposals seek to preserve the original character of the site, using approaches that involve its protection and development (Margottini et al., 2016), with measures proportional to the established safety objectives and the least possible damage to its natural and cultural values.

This approach is in line with the Nature-Based Solutions (NBSs) guidelines, which seek to guarantee the conservation of natural areas and benefit society, mitigating risks and increasing resilience (Villegas-Palacio et al., 2020; Kumar et al., 2021; Vojinovic et al., 2021; Wu et al., 2021).

The application of this approach in the study of instability processes makes it essential to develop strategies for obtaining detailed information of the territory (Abellán et al., 2010; Pham et al., 2016; Fanos and Pradhan, 2019), which allow the development of simulation analyses and accurate modeling (Dorren, 2003; Lan et al., 2007; Stoffel et al., 2010; Keskin, 2013; Ansari et al., 2018), with which to contrast proposals for action adapted to the dynamics of the study environments.

Thus, the present thesis addresses, from specific methodological approaches, the management of rockfall risk, which is one of the most recurrent processes in coastal environments (Rosser et al., 2005; Michoud et al., 2012), in four environments of the Basque coast and one in Liguria, from its detailed study.

The main objective of this thesis is to establish a conceptual framework for the development of integrated strategies for environmentally and socially sustainable risk management in coastal environments with coastal cliffs. These approaches seek to advance the incorporation of nature-based or minimum impact measures, and to document their efficiency alone or in combination, in a combined land and landscape management plan.

Within this general framework, specific objectives can be distinguished as follows:

OBJECTIVE 1. To advance in the characterization, from a geomechanical point of view, of the rocky materials that constitute the cliffs and to recognize the typology of unstable elements depending on the orientation of the cliffs with respect to the rock massif and its discontinuities.

In this sense, geomechanical analysis is a suitable tool to understand the underlying mechanisms driving instability, as there is a clear relationship between the arrangement of discontinuities, their orientation, spacing and persistence, and the typology of breaks (Cooke et al, 2006; Corominas et al., 2017; McGinnis et al., 2017).

This objective is addressed in chapters I, II, III, IV and V, as it results in the first approach to geological materials in working environments.

OBJECTIVE 2. To develop and generate detailed topographic information (DTM, point clouds, orthophotos), to serve as a basis for the development of three-dimensional modeling using satellite LiDAR, Terrestrial Laser Scanning and photogrammetry by Unmanned Aerial Vehicles (UAV or "drone") as appropriate and according to the characteristics and limitations of each study area.

Thus, the research in Italy has been carried out using satellite LiDAR techniques (chapter V), while the rest of the research has been developed using Terrestrial Laser Scanning (chapters II, III, IV) and UAVs (chapter I) on the ground.

OBJECTIVE 3. Monitoring of detachments, magnitude and frequency. Identification, characterization and analysis of rockfall source areas, breakage typology, trajectories, dimensional characteristics and runout of the detached blocks.

This objective has been addressed in chapters I, II, IV and V, in which the evolution of the cliffs is largely developed through continuous rockfalls that can be identified and contextualized according to their spatial and temporal scale.

OBJECTIVE 4. Advance in the use of geotechnical monitoring networks arranged in situ to perform highly accurate continuous monitoring.

This methodology has been specifically implemented in chapter III, in which an evaluation of extremely slow structural movements (Greif et al., 2006) in the long-term has been carried out by means of spectral analysis. These techniques can be extrapolated to other cultural and natural environments.

OBJECTIVE 5. To develop and adapt simulation models for fall trajectories that allow to recognize, as basic parameters, their runout, height and energy along the slopes, including the lateral dispersion of the trajectories. This approach allows advancing in the assessment and validation of the characteristic parameters that condition the evolution of rock fragments in different materials and contexts.

This objective, which is one of the main points of the research carried out, has been developed in chapters I, II, IV and V.

OBJECTIVE 6. Integrate all previous information in precise zoning of susceptibility to rockfall runout, kinetic energy, height and hazard, and evaluate protection and management solutions adapted to each environment, according to its natural and landscape values.

This section has been carried out in chapters I, II, IV and V. Although the study of singular actions to elaborate management plans has been developed according to the particularities of each environment, the approach developed as a whole can be adapted and extrapolated to other areas with similar problems, both coastal and inland, prioritizing the consideration of non-structural measures, combined with prevention, warning and education strategies.

Table 1. Objectives of the doctoral thesis

OBJECTIVES	*Chapter I*	*Chapter II*	*Chapter III*	*Chapter IV*	*Chapter V*
OBJECTIVE 1 Advance in the geomechanical characterization and typology of instabilities	●	●	●	●	●
OBJECTIVE 2 Develop and generate detailed topographic information (DTM, LiDAR, point clouds...)	●	●	●	●	●
OBJECTIVE 3 Detachments monitoring, magnitude and frequency: source areas, trajectories, dimensional characteristics and runout of blocks	●	●		●	●
OBJECTIVE 4 Advancing the use of in-situ geotechnical networks for continuous monitoring of extremely slow movements			●		
OBJECTIVE 5 Develop and adapt three-dimensional rockfall trajectory models	●	●		●	●
OBJECTIVE 6 Integrate the information generated for the elaboration of susceptibility and hazard maps, and to assess protection and management actions	●	●		●	●

3.2. Hipotesi eta helburu orokor eta berariazkoak

Gaur egungo garapen zientifiko eta teknologikoari esker, hainbat motatako jarduerak egin daitezke lurraldean, askotariko ikuspegiekin: eraikuntzako esku-hartze sendoetatik hasi eta kudeaketa iraunkorreko planetara, eragin txikiko tokiko neurriekin ahalik eta inbasibotasun txikiagoa izan nahi dutenak.

Arrokak erortzearen ondoriozko arriskuen kasuan, eraikuntza-hurbilketaren helburua arrisku-maila gutxitzea da, sistema sozioekologikoen ingurumen-alderdietan sakondu gabe (Accastello et al., 2019). Neurri horiek, beharrezkoak izan daitezkeen arren, perturbazio-iturri dira ingurunean (O'Farrell and Anderson, 2010; Rimbock et al., 2014), Donostiako Haizearen Orrazian garatutako ekintzak bezalakoak.

Beste muturrean, ingurumenaren aldetik adiskidetsuak diren proposamenetan (friendly) oinarritutako jarduketen bidez, lekuaren jatorrizko izaera gorde nahi da, hura babestu eta garatzeko hurbilketak erabiliz (Margottini et al., 2016), ezarritako segurtasun-helburuekiko proportzionalak diren neurriekin eta haren balio natural eta kulturalei ahalik eta kalte gutxien eginez.

Hurbilketa hori Nature-Based Solutions-en (NBSak) jarraibideekin lotuta dago. Naturguneen kontserbazioa bermatzea eta gizarteari onura ateratzea dute helburu, arriskuak arinduz eta erresilientzia handituz (Villegas-Palacio et al., 2020; Kumar et al., 2021; Vojinovic et al., 2021; Wu et al., 2021).

Ezegonkortasun-prozesuen azterketan ikuspegi hori aplikatzeko, ezinbestekoa da lurraldearen informazio zehatzak lortzeko estrategiak garatzea (Abellán et al., 2010; Pham et al., 2016; Fanos eta Pradhan, 2019), simulazio-analisiak eta modelizazio zehatzak garatzeko aukera emango dutenak (Dorren, 2003; Lan et al., 2007; Stoffel et al., 2010; Keskin, 2013; Ansari et al., 2018), eta horiekin ikerketa-inguruneen dinamiketara egokitutako jarduera-proposamenak alderatzeko.

Hala, tesi honek, hurbilketa metodologiko berariazkoetatik abiatuta, arrokak erortzeko arriskuaren kudeaketa aztertzen du, hori baita kostaldeko inguruneetan gehien errepikatzen den prozesuetako bat (Rosser et al., 2005; Michoud et al., 2012), euskal kostaldeko lau ingurunetan eta Liguriako batean, xehetasun-azterketatik abiatuta.

Tesi honen helburu nagusia esparru kontzeptual bat ezartzea da, itsasertzeko itsaslabarrak dituzten guneetan ingurumenaren eta gizartearen aldetik jasangarriak diren arriskuak kudeatzeko estrategia integratuak garatzeko. Hurbilketa horien bidez, naturan edo inpaktu minimoan oinarritutako neurriak txertatu nahi dira, eta haien eraginkortasuna bakarrik edo konbinatuta dokumentatu, lurraldea eta paisaia batera kudeatzeko plan batean.

Esparru orokor horretan, helburu espezifiko hauek bereiz daitezke:

1 HELBURUA. Itsaslabarrak osatzen dituzten material harritsuen karakterizazioan aurrera egitea, ikuspuntu geomekanikotik, eta elementu ezegonkorren tipologia ezagutzea, labarrek mendigune harritsuaren eta haren etenuneen inguruan duten orientazioaren arabera.

Alde horretatik, azterketa geomekanikoa tresna egokia da ezegonkortasuna bultzatzen duten azpiko mekanismoak ulertzeko, erlazio argia baitago etenguneen antolaketaren, orientazioaren, tartekapenaren eta jarraitutasun eta hausturen tipologiaren artean (Cooke et al., 2006; Corominas et al., 2017; McGinnis et al., 2017).

Helburu hori I., II., III., IV. eta V. kapituluetan lantzen da, lan-inguruneetako material geologikoetara lehenengo hurbilketa baita.

2 HELBURUA. Informazio topografiko zehatza garatzea eta sortzea (MDT, puntu-hodeiak, ortofotoak), modelizazio tridimentsionalen garapenerako oinarria izango dena satelite bidezko

LiDAR, Lurreko Eskaner Laser eta fotogrametria Tripulatu Gabeko Aireko Ibilgailuen (TGAI edo “drona”) bidez, kasuaren arabera, eta azterketa-eremu bakoitzaren ezaugarriak eta mugak kontuan hartuz.

Horrela, Italiako ikerketa sateliteetako LiDAR tekniken bidez egin da (V. kapitulua); gainerako ikerketak, berriz, Lurreko Laser Eskanerraren (II., III., IV. kapituluak) eta TGAI-en (I. kapitulua) bidez egin dira landan.

3 HELBURUA. Luizien jarraipena, magnitudea eta maiztasuna. Arrokak erortzeko iturri diren eremuak, haustura-motak, ibilbideak, dimentsio-ezaugarriak eta eroritako blokeen irismena identifikatu, karakterizatu eta aztertzea.

Helburu hori I., II., IV. eta V. kapituluetan landu da. Kapitulu horietan, labarren bilakaera, neurri handi batean, luizi jarraituen bidez garatzen da. Luizi horiek beren espazio- eta denbora-eskalaren arabera identifikatu eta testuinguruan kokatu daitezke.

4 HELBURUA. In situ jarritako kontrol geoteknikoko sareen erabileran aurrera egitea, doitasun handiko segimendu jarraituak egiteko.

Metodologia hori III. kapituluan ezarri da zehazki. Kapitulu horretan, oso motelak diren egitura-mugimenduen ebaluazioa egin da (Greif et al., 2006) epe luzera (long-term), espektro-analisien bidez. Teknika horiek beste ingurune kultural eta natural batzuetara estrapola daitezke.

5 HELBURUA. Erorketen ibilbidea simulatzeko ereduak garatzea eta egokitzea, isurkietan zehar duten irismena, altuera eta energia oinarrizko parametro gisa ezagutzeko, ibilbideen alboko sakabanaketa barne. Hurbilketa horri esker, arroka-zatien eboluzioa baldintzatzen duten parametro karakteristikoak baloratzen eta egiaztatzen aurrera egin daiteke, hainbat material eta testuingurutan.

Helburu hori egindako ikerketaren puntu nagusietako bat da, eta I., II., IV. eta V. kapituluetan garatu da.

6 HELBURUA. Aldez aurreko informazioa sartzea, harri-jausien irismenari, energia zinetikoari, altuerari eta arriskugarritasunari buruzko zonifikazio zehatzetan, eta ingurune bakoitzera egokitutako babes- eta kudeaketa-soluzioak baloratzea, natur eta paisaia-balioen arabera.

Atal hau I., II., IV. eta V. kapituluetan egin da. Kudeaketa-planak egiteko jarduera berezien azterketa ingurune bakoitzaren berezitasunen arabera garatu den arren, oro har garatutako hurbilketa antzeko arazoak dituzten beste gune batzuetara egokitu eta estrapolatu daiteke, bai itsasertzera, bai barnera, eta lehentasuna eman dakioke egiturazkoak ez diren neurriei, prebentzio-, alerta- eta hezkuntza-estrategiekin konbinatuta.

1.taula. Doktorego tesiaren helburuak

HELBURUAK	*I. Kapitulua*	*II. Kapitulua*	*III. Kapitulua*	*IV. Kapitulua*	*V. Kapitulua*
1. Helburua Karakterizazio geomekanikoan eta ezezgonkortasunen tipologian aurrera egitea	✓	✓	✓	✓	✓
2. Helburua Detailezko informazio topografikoaren sorkuntza (DTM, LiDAR, hodei-puntuak...)	✓	✓	✓	✓	✓
3. Helburua Luizien jarraipena, magnitude eta maiztasuna: iturburu-eremuak, ibilbideak, dimentsio espezifikoak eta blokeen irismena	✓	✓		✓	✓
4. Helburua In situ sare-geoteknikoen erabileran aurrera egitea, mugimendu oso motelen monitoring-a egiteko			✓		
5. Helburua Harri-jausien ibilbide hiru-dimentsioko modeloen garapena eta egokitzea	✓	✓		✓	✓
6. Helburua Sortutako informazioa suszeptibilitate- eta arriskugarritasun mapak garatzeko, babes eta kudeaketako aktuazioak baloratzea	✓	✓		✓	✓

4.1. Capítulo I: Analysis of instabilities in the Basque Coast Geopark coastal cliffs for its environmentally friendly management (Basque-Cantabrian basin, northern Spain)

Acantilados costeros de la playa de Itzurun (Zumaia)

Tomás Morales, **Jon Ander Clemente**, Laura Damas Mollá, Eñaut Izagirre, Jesus A. Uriarte

Engineering Geology
Volume 283, 20 March 2021, 106023
https://doi.org/10.1016/j.enggeo.2021.106023

Abstract

Coastal cliffs provide a high landscape value to many natural sites around the world. This means that an ever-increasing number of people are attracted to them. At this point, there is a growing need to manage these spaces from the safety of visitors, but with a view to preserving the environment. With this aim, this paper presents an approach to analyze and manage instabilities in these environments, particularly those subjected to significant anthropic activity, which has been implemented in the cliffs of the Basque Coast Geopark. The starting point is a detailed topographic information, obtained from UAV flights, and the identification on site of unstable elements, including their typology, active source areas, dynamics and reach. From this information, the simulation of rockfall processes, which basically correspond to toppling and infinite slope instabilities favored by differential erosion along the coastline, is approached in two and three dimensions. Results allow the design of precise actions by sectors, according to the energy, height and reach of the detached blocks, including barriers, middle slope actions, ditches and information strategies, depending on the different uses of the sectors. Therefore, this approach leads to a more detailed and environmentally friendly management of these environments**.**

Keywords: Coastal cliffs; Stability analysis; 2D-3D simulation; Friendly management; Basque Coast Geopark.

1. Introduction

Coastal cliffs are geological-geomorphological elements that give rise to unique landscapes of high scientific, cultural and social value on coasts around the world (Emery and Kuhn, 1982; Panizza, 2001; Kubalíková, 2013; Kirchner and Kubalíková, 2013; Kirchner and Kubalíková, 2015; Young, 2018). Defined as a steeply sloping surface where elevated land meets the shoreline (Hampton and Griggs, 2004), constitute about 80% of the world seashore (Emery and Kuhn, 1982). Rising above the geological outcrops developed on a wave-cut platform, upon beaches or directly over the sea (Trenhaile, 2010; Sunamura, 2015) are affected by different marine and subaerial processes (Alessio and Keller, 2020), including waves (Young et al., 2011), groundwater flow (Pierre and Lahousse, 2006), mechanical and chemical weathering (Porter and Trenhaile, 2007) and rainfall (Collins and Sitar, 2007); while acting as conditioning factors the cliff lithology (Sunamura, 1992), coast geometry (Hampton and Griggs, 2004) and structural characteristics (Duperret et al., 2004).

Some of them are recognized and recognizable natural settings that attract an increasingly large audience. A particularly significant example of this situation is the Basque Coast Geopark (Geoparkea).

This protected area extends over 14 km from the eastern coast of the Basque Country (northern Spain). It is dominated by cliffs, with outcrops of high geological value, as evidenced by the award of two golden spikes ratified in 2010 by the International Commission on Stratigraphy (ICS), part of the International Union of Geological Sciences (IUGS). In November 2010, it joined the European and Global Network of Geoparks, which brings together sites of international geological importance, managed with values of conservation, education and sustainable development (Black and Gonggrijp, 1990; Brilha, 2002; Andrasanu, 2009; Henriques et al., 2011; Wimbledon and Smith-Meyer, 2012; Brilha, 2018).

Within this protected environment, the most visited sectors are those corresponding to the beaches of Itzurun and Algorri, together with the cliffs around the village of Zumaia. Given that the Basque coast is predominantly erosive, these beaches attract significant summer tourism. In addition, cult films and series have been filmed in the area in recent times, which has led to a significant increase in the number of visitors throughout the year.

It is a natural environment of active dynamics, where coastal cliffs evolve through gravitational processes, with the development of different forms of instability, resulting in rockfalls (Canuti et al., 2009), which is one of the most recurrent processes in coastal environments (Rosser et al., 2005; Michoud et al., 2012).

In this context, the need arises to know in detail the evolutionary processes that condition safety in the area. To this end, it is essential to analyze the factors and conditions of their origin (Luckman, 2013; Hernández-Gutiérrez and Santamarta, 2015), with the aim of carrying out specific risk management (Glade, 2003; Crosta and Agliardi, 2004; Frattini et al., 2008, Frattini et al., 2012). However, unlike usual slope engineering projects, conservation and stabilization attempts in environments of recognized natural and cultural value must not only address the damage that may be generated, but also the need to maintain their natural condition when intervening on the site (Guo et al., 2009; Margottini and Vilímek, 2014; Morales et al., 2018).

The work therefore acquires a new complexity (Margottini et al., 2016), since the measures and ways of acting must be effective, to solve the problem; non-invasive, to preserve the original aspect of the site; and feasible with the use of techniques that involve the protection and development of the environment. The nature and purpose of these measures can be completed with the recommendations of the ICOMOS (2003), among which it can be highlighted that each intervention should be proportional to the previously established safety objectives, and limited to the minimum necessary to guarantee the safety and durability of the property, with the least possible damage to the heritage values. An additional recommendation would be that the actions be reversible. The implementation of this approach in the study of instability processes requires a detailed information about the terrain (Abellán et al., 2010; Pham et al., 2016; Fanos and Pradhan, 2019) to develop precise simulation and modeling analyzes (Dorren, 2003; Lan et al., 2007; Stoffel et al., 2010; Keskin, 2013; Ansari et al., 2018), which will allow the proposals for action to be adjusted to the dynamics of the environment under study.

In our work, we seek to make progress in the recognition of instability processes in the Basque Coast Geopark (Geoparkea), which preserves a natural environment including Itzurun and Algorri beaches, with the aim of proposing environmentally friendly management strategies and protection measures in this protected area.

2. Geoparkea Study area

The Basque Coast Geopark (Geoparkea) is located in the Bay of Biscay, to the west of the Pyrenees, and covers the villages of Deba, Mutriku and Zumaia (Fig. 1) (https://geoparkea.eus/es/).

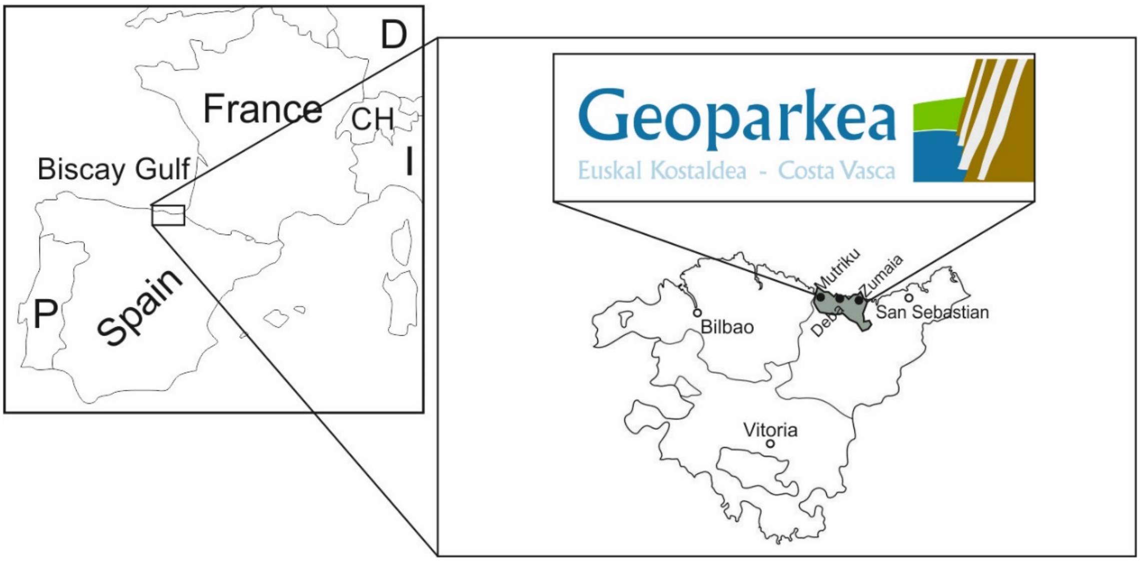


Fig. 1. Geographical context of the Basque Coast Geopark.

Geologically (Fig. 2), this Geopark is located in the so-called Basque-Cantabrian basin (Feuillée and Rat, 1971; Ramírez del Pozo, 1973). There, in a basin-bottom marine environment, thick sedimentary series were deposited during the Lower Cretaceous - Eocene, characterized by a persistent and well-defined stratification, with a great lateral continuity. During the Alpine Orogeny, these materials underwent a notable deformation, giving rise to a mountainous relief that constitutes the western continuation of the Pyrenean mountain range (Arz et al., 1992; Baceta et al., 2012; Barnolas and Pujalte, 2004).

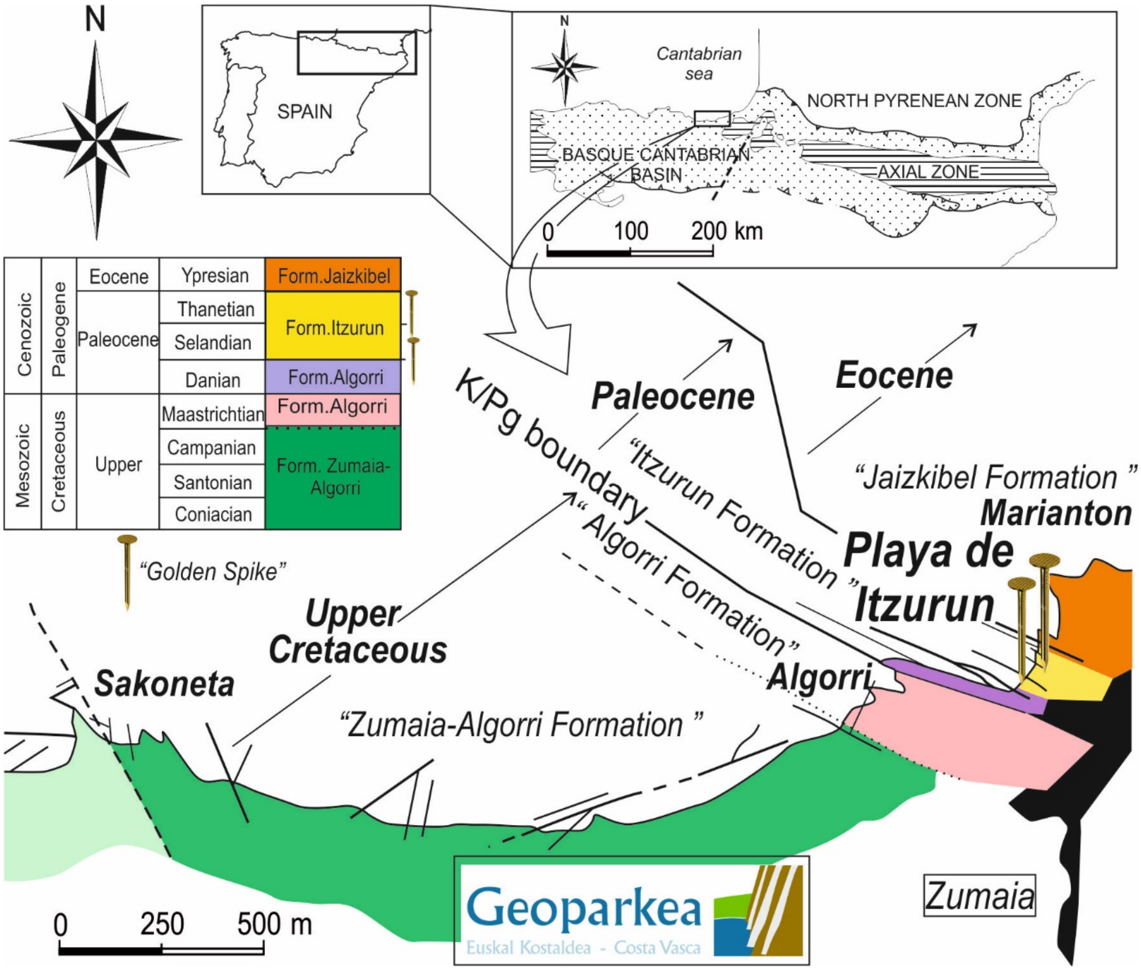


Fig. 2. Sketch map of the main structural features of the Pyrenean belt (modified from Boillot and Capdevila, 1977) and geological map of the studied zone in the Basque Coast Geopark (modified from Baceta et al., 2012).

Specifically, the study area corresponds to the coastline between Deba (Sakoneta) and Zumaia, where the geological record is practically continuous from the Maastrichtian (Upper Cretaceous) to the Ypresian (Lower Eocene). The subvertical arrangement of the flyschoid successions allows a precise analysis of them, which concluded with the award of two golden spikes in 2010, a fundamental milestone for the declaration of this space as part of the Global Geoparks Network. Both milestones are located at the Itzurun beach (Zumaia). To the east of it, the boundary between the Danian and the Selandian, associated with a drop in sea level (Orue-Etxebarria et al., 2007; Arenillas et al., 2008; Bernaola et al., 2009), is the first of the two strata marked with the “golden spike”. Further to the northeast is the Itzurun Formation, in which the stratotype for the Selandian-Thanetian boundary (golden spike), defined by an inversion in the Earth's magnetic field (Pujalte et al., 1995; Schmitz et al., 1998; Schmitz et al., 2011), has also been awarded.

With respect to the hydrodynamic setting, the study area is exposed to large storms and preferential winds from the NW, which develop waves to SE orientation that dominate all the Basque Coast (Galparsoro et al., 2010; Bilbao-Lasa et al., 2020). These waves rarely exceed 5 m high, and the most habitual height is between 1 and 2 m for summer and 2–5 m for winter. The tidal wave is semi-diurnal and the main tidal range along the Basque Coast is approximately 1.65 m on neap tides and 4.01 m on springs (REDMAR, 2005).

The current landscape is made up of coastal cliffs with heights of between 30 and 70 m that stand out on a coastline dominated by the current wave-cut platforms (Genna et al., 2005; González-Amuchastegui et al., 2005; Pedoja et al., 2014). Coastal dynamics condition that, in areas protected from the action of waves and marine currents, beaches such as the aforementioned Itzurun beach are developed (Bird, 2000; Álvarez-Marrón et al., 2008; Gutiérrez-Elorza, 2008). These are, however, localized and scarce geomorphological elements, and hence they concentrate notable summer tourism. This combination of landscape, geological and leisure values, has led to a growing influx of general and specialized tourism into the area, which is why the study of stability and safety of the cliffs and their management in a high-value environment is a challenge and a necessity.

3. Methodology

3.1. Detailed topographic information

The first phase of the work consisted of obtaining a detailed image of the terrain, for which we acquired aerial imagery using a commercial DJI Mavic Pro 2 drone or unmanned aerial vehicle (UAV). The UAV is equipped with a 20 Megapixel digital compact camera with a fixed 28-mm lens and we added a Reach M+ RTK (Real Time Kinematic) device that was in continuous radio communication with a base EMLID Reach RS+ station. This technique is widely used for topography, where a single reference station provides corrections to a rover device in real time, obtaining a submetric accuracy (Raquet and Lachapelle, 2001; Wu et al., 2019; Valente et al., 2020).

The UAV was launched from the highest parts of the cliffs at 40 m above launch points, and the survey plan, designed with the assistance of a 1 m resolution LIDAR mosaic, provided a consistent flight altitude of ~80 m above sea level and a ground sampling distance (GSD) of ~3 cm per pixel. Flights were planned with the flight planning software Pix4Dcapture and the UAV flight speed was set to 6 m/s. For all flights, the overlap of both front and side images was set to be 70%, although the real overlap is supposed to be even larger because most of the modelled terrain lies lower than the UAV launching points from the highest part of the cliffs.

Photogrammetric outputs were calculated from images and camera positions using Agisoft Metashape Professional v1.6.3 software (https://www.agisoft.com/). Processing workflow and parameters were set according to official Agisoft guidelines (Agisoft, 2018), and Structure from Motion (SfM) algorithm was used to create the final dense point cloud, from where the orthomosaics at 0.15 m resolution and geoid-corrected Digital Terrain Models (DTMs) at 0.20 m resolution were derived. The SfM technique is highly employed in the field of geosciences (Westoby et al., 2012; Jing et al., 2017; Feurer and Vinatier, 2018), which allows obtaining a high-resolution data, capable of representing a 2D to 3D object with a series of photographs from different points of view (Tomás et al., 2016; Kim et al., 2018; Garrido-Carretero et al., 2019; Zhang et al., 2020) (Fig. 3).

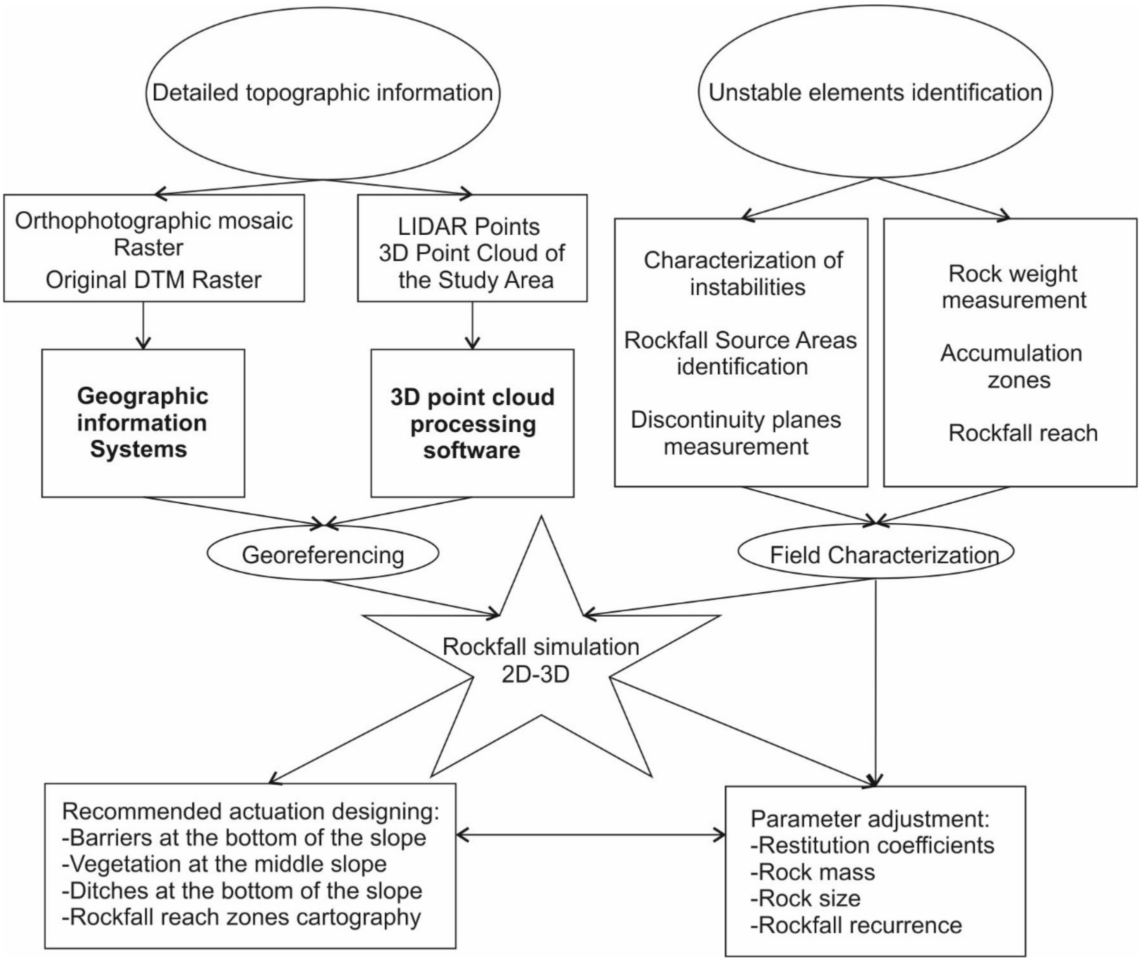


Fig. 3. Methodological flow chart.

3.2. Identification of unstable elements

Instabilities are identified directly on site, through monthly visits during the last 2 years, which were documented photographically. Survey is completed, particularly in not accessible areas, with the images of the UAV. Fieldwork also includes the characterization of materials and discontinuity network that affect the rock mass. This network gives rise to a structure of planes of weakness that determine the shape and size of the unstable elements. Furthermore, their orientation with respect to the cliffs determines the dynamics of the instabilities. Its characterization includes the measurement of the orientation of the discontinuity planes and their geomechanical characteristics (roughness, filling, opening and spacing) (Fraternali, 2007; Zhang et al., 2018; Kong et al., 2020). Based on these measurements, the different discontinuity families of slope are established, and a kinematic analysis of instabilities in stereographic projection is performed. In our case, RocScience's Dips.v.6.0. software (RocScience, 2013) is used to facilitate data processing. With this information, the types of instabilities, active rockfall source areas, evolution and reach are defined.

At the same time, a specific recognition of the detached blocks was carried out, which includes the collection of data on their weights and morphologies, fall trajectories and reaches. The determination of weights was done with two KAMER model dynamometers: one for rocks up to 25 kg, with an accuracy range of +/− 20 g; the other for rocks up to 150 kg, with an accuracy range of +/− 100 g. The size of the rocks was obtained with a measuring tape that the same dynamometer incorporates. The weight and dimensional measurements were made on the rocks deposited at the foot of the slope, along with the quantification of the number of falls, their reach, the areas of influence and, where observable, the entity of impacts. This section also included information provided by technicians from the Geopark and the City Council.

3.3. Modeling and simulation of rockfalls

The evolution in the terrain of detached rock fragments is controlled by the dissipation of their energy, which is usually approximated by two coefficients (Pfeiffer and Bowen, 1989): the normal restitution coefficient (RN), which indicated the degree of elasticity in a normal collision with the slope; and the tangential restitution coefficient (RT), which is a measure of the resistance to the movement parallel to the slope. From both parameters, and after establishing the impact angle, the resulting velocity components can be obtained from the equations

(Pfeiffer and Bowen, 1989; Budetta and Santo, 1994; Spadari et al., 2013; Asteriou, 2018; Rebouças et al., 2019; Jiang et al., 2020; Li et al., 2020; Wang et al., 2020):

Reflected normal velocity ($v_{n,r}$):

$$v_{n,r=} = \frac{v_{n,i} \cdot Rn}{1+\left(\frac{|v_{n,i}|}{K}\right)^2} \qquad (1)$$

Where:

$v_{n,i}$= incident normal velocity,

K=empirical reference velocity

Reflected tangential velocity($v_{t,r}$):

$$v_{t,r=}\sqrt{\frac{R^2 \cdot \left(I \cdot \omega_{(1)}{}^2 + m \cdot v_{t,i}{}^2\right) \cdot FF \cdot SF}{I + m \cdot R^2}} \qquad (2)$$

Where:

R = radius of the rock

$\omega_{(1)}$= initial rotational velocity

m= rock mass

$v_{t,i}$= initial tangential velocity

FF= friction function

SF =scaling factor

I = rock moment of inertia.

Considering the final rotational velocity ($\omega_{(2)}$) as:

$$\omega_{(2)} = \frac{v_{t,r}}{R} \qquad (3)$$

With a friction function (FF), that considered the energy loose in the collision:

$$FF = \frac{1 - R_T}{1.2 + \left(\frac{v_{t,i} - R \cdot \omega_{(1)}}{k_1}\right)^2} \qquad (4)$$

And a scaling factor (SF):

$$SF = \frac{R_T}{1+\left(\frac{v_{n,i}}{k_2 \cdot Rn}\right)^2} \qquad (5)$$

Where k_1 and k_2 are empirical reference velocities.

3.3.1. Three-dimensional (3D) rockfall simulation

The rockfall simulation process was approached by using RocPro3D software. This software performs three-dimensional simulations of individual trajectories from a Digital Terrain Model (DTM), which is extracted from the three-dimensional point cloud obtained by the drone. The same software allows the generation of a three-dimensional terrain mesh by triangulation. The mesh is the basis on which the simulation of rockfall from the identified source areas is carried out.

The main advantage of this model, according to the comparative study conducted by Li and Lan (2015), is that it allows the relief to be considered in three dimension, including the lateral evolution of the trajectories in the simulation. On the contrary, it does not allow modifications to the relief, since it works with the topographic information obtained previously.

3.3.2. Two-dimensional (2D) rockfall simulation

Once the general 3D simulation process is completed, in those cases where fall profile modification is considered, the process is studied locally with RocScience's RocFall software. This software allows performing individualized rockfall simulations (Frattini et al., 2012; Dorren et al., 2013), based on the previously defined 3D fall trajectories. In our approach, the main advantage it brings, is that it makes possible to vary the topographic profile (Li and Lan, 2015) and thus to observe its effect on the evolution of materials. In this 2D simulation process, the topographic profiles previously generated by the RocPro3D software were considered.

3.3.3. Validation of results and proposals for action

The results were contrasted with field observations, allowing to check the similarities and differences between the observed data and the simulated ones, and to adjust the calculation parameters of the models.

Once the detailed modeling of each reference area was achieved, and the types of failure, their reach and energy were established, specific actions to minimize the negative effects of rockfalls can be simulated. In our work, we consider actions that respect the environment, including barriers at the foot of the cliffs in sensitive areas (access area), which can be complemented with middle slope actions and ditches, and information measures at the beach, once the characterization of rockfalls got completed.

4. Results

4.1. Characterization of the instabilities in the study area

At Itzurun beach (sector 1, Fig.4a), the general strata orientation, S0: 80/010, is mainly perpendicular to the coastline (Fig.4a, b), with steep dips towards the northeast. The geological materials are arranged in alternating layers of different competition (flysch sequences), which limits the development of the discontinuity planes that affect the massif; in fact, only the stratification (S0) presents large developments (over 40 meters), while the rest of the weakness planes generally present developments of less than a meter. Specifically, these are the families of joints J1: 70/285, oriented to the beach, and J2: 20/110, oriented to the inside of the massif (fig.4a). This orientation of discontinuities is in principle favorable to slope stability and makes the instability processes to be limited, in general, to moderate falls of rock fragments of small dimensions (Table 1) that evolve over J1. However, differential erosion results in a succession of headlands and inlets, of different dimensions, which give rise to two types of secondary slopes. One, developed at the top of the most resistant layers, with the same dip as the stratification (obverse), and the other on the opposite side of the overhang (reverse). In the first case, the front of the slope is the resistant stratum, in principle stable, although small infinite slope type failures may develop (Table 1). On the reverse side, the resistant materials give rise to an overhanging slope that favors the development of abundant rock fragment topplings (Table 1), which are the main instability processes on the cliffs surrounding Itzurun beach.

Table 1
Typology and main characteristics of instabilities by sectors

		Dip	**Dip Direction**	**Type**	**Recurrence***	**Size****
Sector 1 Itzurun beach	General slope	80	280	Rock Plane	Moderate	Small
	Obverse slope	75	030	Infinite Slope	Low	Medium
	Reverse slope	50	200	Toppling	Very high	Medium
Sector 2 Archs	General slope	65	020	Infinite Slope	Exceptional	Extraordinary
Sector 3 Algorri beach	North slope	70	010	Toppling	High	Large
	South slope	75	240	Infinite Slope	Exceptional	Extraordinary
Sector 4 Itzurun txiki	General slope	80	280	Rock Plane	Moderate	Small
	Obverse slope	75	030	Infinite Slope	Low	Medium
	Reverse slope	50	200	Toppling	Very high	Medium
PuntaMariantón	South slope	80	190	Massive Slide	Exceptional	Extraordinary

*Recurrence: Exceptional: less than 1 per more than 5 years; Very low: less than 10 per 1-5 years; Low: less than 10 per year; Moderate: less than 10 per month; High: less than 10 per week; very high: more than 10 per week

**Size: Small: <1 dm^3; Medium: 1-5 dm^3; Large: > 5-25 dm^3; Very large: > 25 dm^3; Extraordinary: several m^3

To the south of Itzurun beach, differential erosion has given rise to a sharply headland (sector 2, Fig.4a, c) developed over competent materials. The erosive action of the waves has generated in its front some characteristic arch morphologies that constitute one of the most recognizable images of the geopark. The general geological structure is favorable to stability; however, in recent times an infinite slope failure of a stratum plate of 30 cm thickness and several meters of development has been recorded.

Further south of the Itzurun beach, the small beach of Algorri (sector 3, Fig.4a, d) draws a small inlet flanked by two cliffs that present the typology of failures described for Itzurun. Nevertheless, in a more erosive environment, the development of instabilities is of greater entity. Thus, on the northern slope, where the K-Pg boundary is located, the conditions for the development of topplings are very favorable and the fall of blocks of moderate size is relatively frequent. In the southern slope, developed at the top of a competent layer, an infinite slope failure of similar dimensions to those of sector 2 has been recorded in recent times.

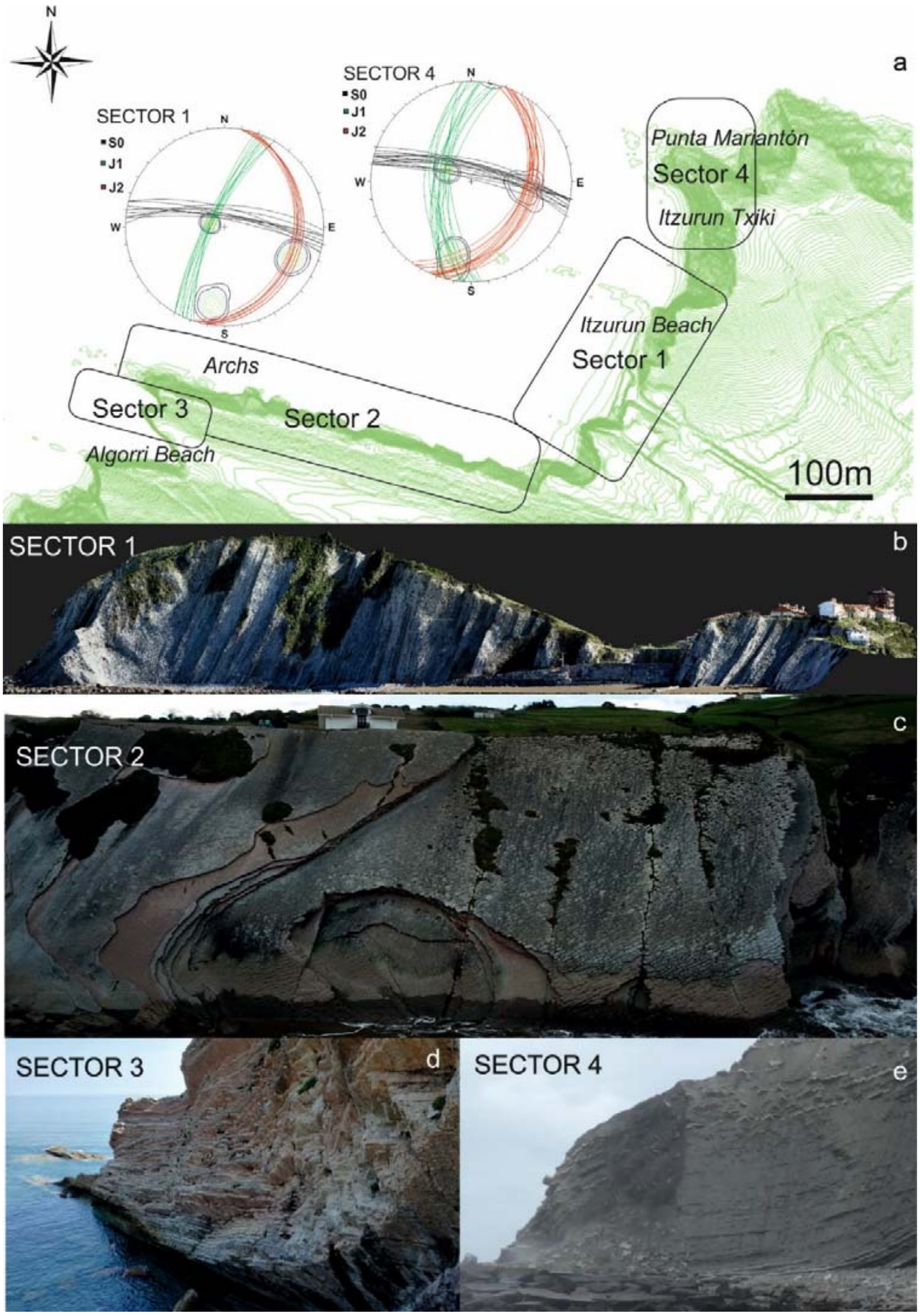


Fig.4. a) Sectors differentiated in the study area: b) Itzurun beach: corresponds to the area of the most use, where a large part of the summer tourism is concentrated; c) Archs: the beach is framed by spectacularly developed cliffs marked by the presence of large natural arches; d) Algorri beach: where the K/Pg boundary outcrops; e) Punta Mariantón: characterized by coastal cliffs over a wave-cut platform.

Finally, to the north of Itzurun beach (sector 4: Itzurun Txiki, Fig.4e), the flyschoid sequence is similar to sector 1; the main difference with the previous one is that it runs along a wave-cut platform, so the base of the cliffs is of a highly erosive nature. Towards the north, the series become marlier in general and the presence of a smaller number of competent levels is a fundamental factor that determines the development of massive breaks in Punta Mariantón (Fig.4e).

4.2. Analysis of rockfall at Itzurun beach

4.2.1. Characterization of instabilities

Once the general reconnaissance of the area had been carried out, the work focused on the analysis of falls on the cliffs bordering Itzurun beach (sector 1). This is the most visited area, as well as the one where the accesses to the beach are located.

There, the origin areas of the main rockfalls or source areas have been identified, determining their height, development, materials involved and landslide marks (Fig.5a). At the bottom of the slope, the number of accumulated blocks, their location, origin, reach, impact and damage are identified (Fig.5a).

As far as the evolution of the blocks is concerned, some of the rockfalls evolve from the general slope in a largely direct path, even though the most frequent movements start with a toppling from the secondary obverse slope and draw a more complex evolution towards the foot of the reliefs.

Altogether, a total of 363 rocks were weighed in the accumulation areas. From this information, an overall bar diagram was elaborated that allows to observe that most of the fragments have a weight lower than 500 N, and 80% are lower than 100 N. Locally, blocks of more than 5000 N were identified, which represent less than 0.01% of the total (Fig.5b). The smaller and consequently lighter fragments come mainly from the marlier layers of the series, while the larger materials come from the more competent ones.

With regards to the reach of the detached fragments is concerned, most of the falls are of limited dimensions and the blocks remain accumulated at the foot of the slope. However, some fragments evolve to the access area and to the beach. Their reach, measured from the baseline of the slope, does not exceed 10 meters. They are precisely the problems associated with these falls that make it necessary to analyze in detail their dynamics, reach and energy, with a view to designing friendly interventions that prevent damage without substantially disturbing the environment.

For the detailed analysis of the detached blocks, the sector of Itzurun beach has been divided into 8 zones (Fig.5). In each of these, the evolution of materials is simulated on the DTM obtained previously. In the areas with a high number of fallen blocks, a statistical analysis of their weight was carried out and the characteristic parameters of their distribution were obtained. As an example, in areas F and G, the blocks coming from the most competent levels, which present greater size and energy, are adjusted to a normal distribution (Fig.6). From this, the mean and a superior characteristic value, that includes the 95% of sample weights were calculated (Bond and Harris, 2008). Specifically, in the examples of figure 6, for a number of samples n = 54 and 70, the corresponding characteristic weight values (tn-195%) are 824 N and 578 N, respectively. In the areas with a smaller number of blocks, the simulations have been carried out with the maximum-recorded sizes.

As for the characteristic parameters of the materials in the slope, they are calibrated to reproduce the trajectories and reach of rock fragments recognized in the fieldwork. In our approach, 4 types of terrain have been considered in the modeling: flysch, beach, vegetation and access. The characteristic coefficient of restitution, rebound and friction obtained from the adjustment process are shown in table 2.

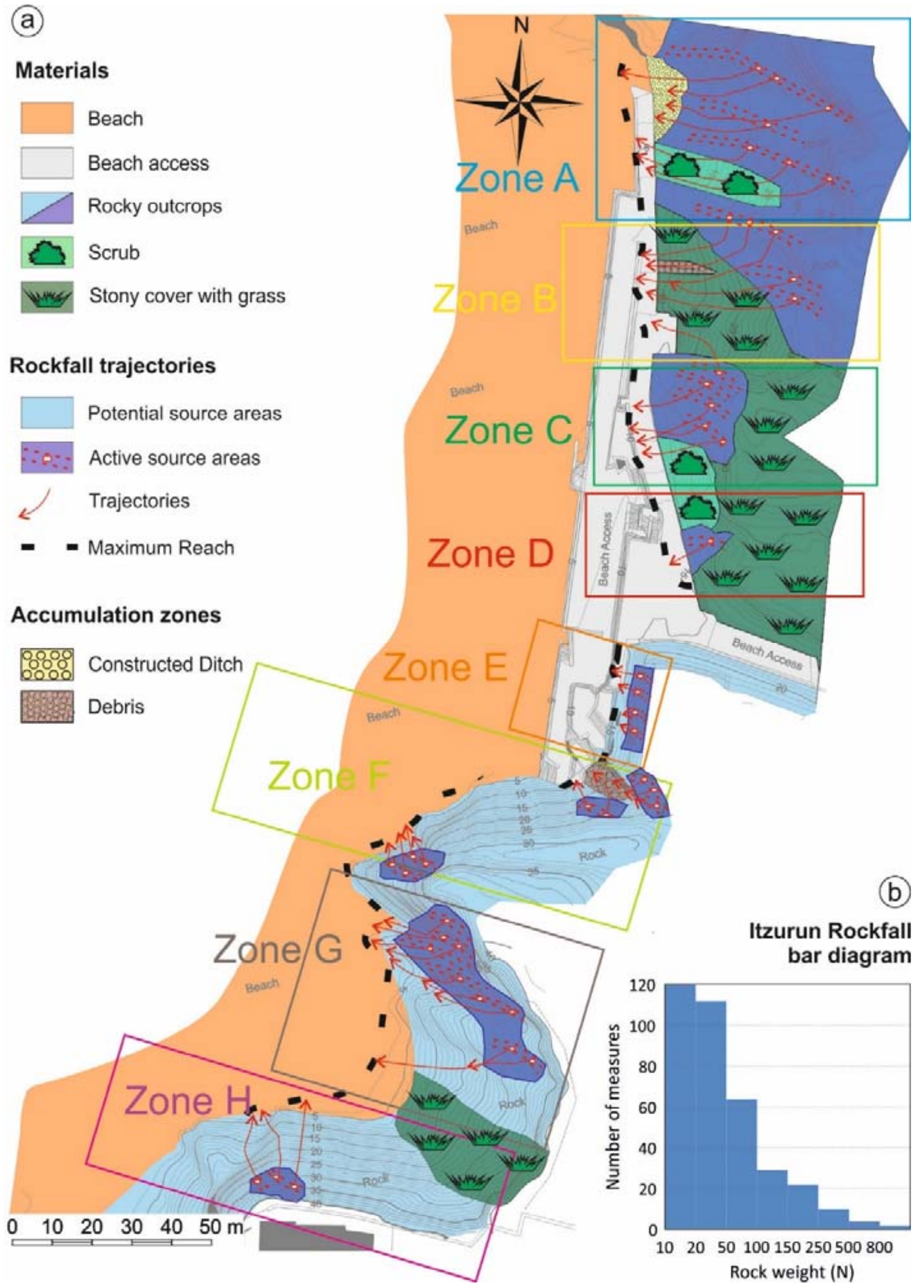


Fig. 5. Rockfall basic information: a) source areas, trajectories and reach of rockfalls at the Itzurun beach; b) bar diagram by weight of fell rocks.

4.2.2. Modeling

From these values, possible random deviations are considered, following Gaussian distributions with the standard deviation values predefined in the RocPro3D program (Table 2).

With the above-mentioned parameters of rock weight, source area and zero initial speed, on the one hand, and those of the four terrains, on the other hand, we proceed to the launch of 100 rockfall simulations per source area, obtaining a wide representation of trajectories.

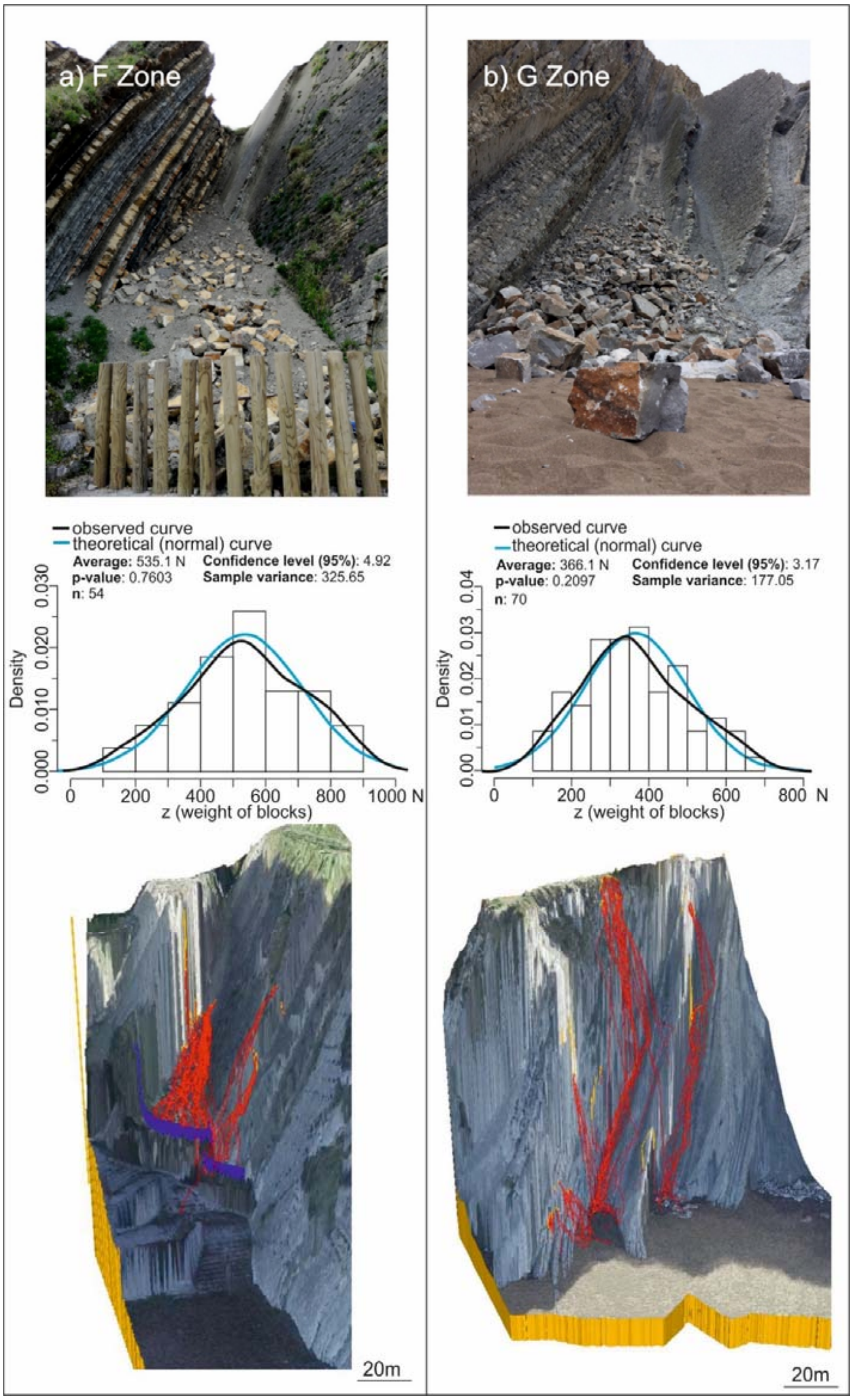


Fig. 6. Photographs, normality analysis and three-dimensional simulations of the F (a) and G (b) zones.

Table 2
Terrain adjusted parameters and random deviations considering Gaussian distributions

Factor	Material	Type	Parameter	Adjusted Value	Prob. Gaussian (μ,σ)
Soil properties	Flysch	Sliding/Rolling	Dynamic friction (k)	0.45	0.45, 0.045
		Impact	Normal Coefficient of restitution (Rn)	0.6	0.6, 0.011
			Tangential Coefficient of Restitution (Rt)	0.9	0.9, 0.011
			Lateral deviation (º)	0	0, 10
			Rebounds flattening (º)	0	0, 1
	Beach	Sliding/Rolling	Dynamic friction (k)	0.5	0.5. 0.036
		Impact	Normal Coefficient of restitution (Rn)	0.3	0.3, 0.012
			Tangential Coefficient of Restitution (Rt)	0.8	0.8, 0.012
			Lateral deviation (º)	0	0,5
			Rebounds flattening (º)	0	0, 1
	Access	Sliding/Rolling	Dynamic friction (k)	0.6	0.6, 0.036
		Impact	Normal Coefficient of restitution (Rn)	0.6	0.6, 0.0125
			Tangential Coefficient of Restitution (Rt)	0.8	0.8, 0.0125
			Lateral deviation (º)	0	0, 8.75
			Rebounds flattening (º)	0	0, 1
	Vegetation	Sliding/Rolling	Dynamic friction (k)	0.45	0.45, 0.045
		Impact	Normal Coefficient of restitution (Rn)	0.3	0.3, 0.012
			Tangential Coefficient of Restitution (Rt)	0.8	0.6, 0.0125
			Lateral deviation (º)	0	0, 5
			Rebounds flattening (º)	0	0, 1

For the whole sector, the maximum energy values were obtained in zone G (table 3, Figs. 5, 6 and 7), where 12 kJ were computed. In the rest of the zones, except for zones A and F, where values of up to 5 kJ were achieved, the maximum values were around 2 kJ (Table 3). The maximum reaches were obtained in zone A and G, with values up to 10 meters from the baseline of the slope (Fig.7). In zones E and F, the current presence of barriers limit the reach of rockfalls.

Table 3
Energy and reach of rockfalls by zones. In zones E and F the reach is limited for barriers.

ITZURUN	ZONE A	ZONE B	ZONE C	ZONE D	ZONE E	ZONE F	ZONE G	ZONE H
Energy (kJ)	3-4	1.5-2.5	0.8-1	0.2	0.2	4-5	12	0.5
Reach (m)	8-10	3-5	3-5	1-2	Barrier	Barrier	8-10	3-5

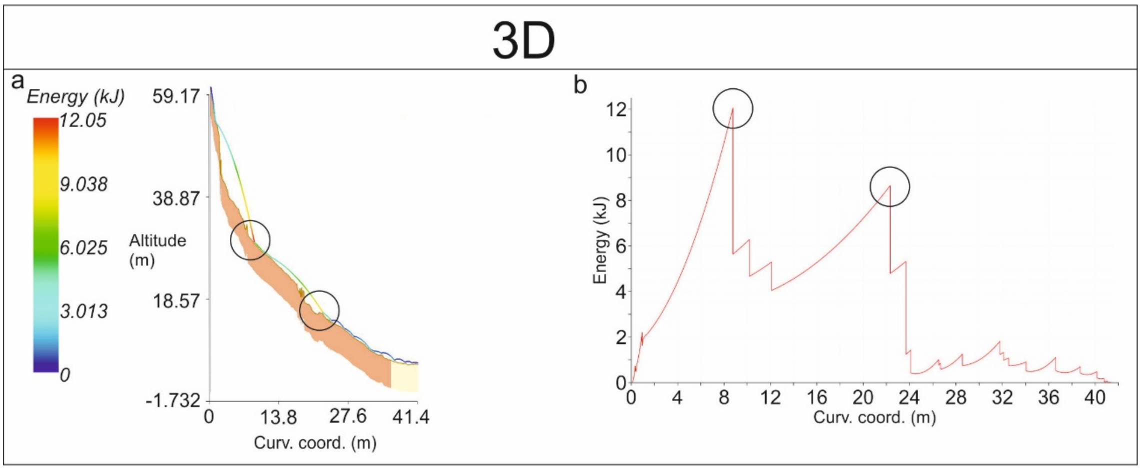


Fig. 7. Individualized analysis of trajectories in the G zone of Itzurun

4.3. Mitigation measures

Unlike usual slope engineering projects, conservation and stabilization efforts in environments of high landscape and environmental value must not only deal with the damage that may be generated, but also with the need to observe the principle of maintaining their natural condition when intervening on the site (Guo et al., 2009).

In accordance with these criteria, the following main mitigation measures are considered in the Basque Coast Geopark:

-Removing loose materials on the cliffs and slopes around Itzurun beach, with the elimination of unstable elements.

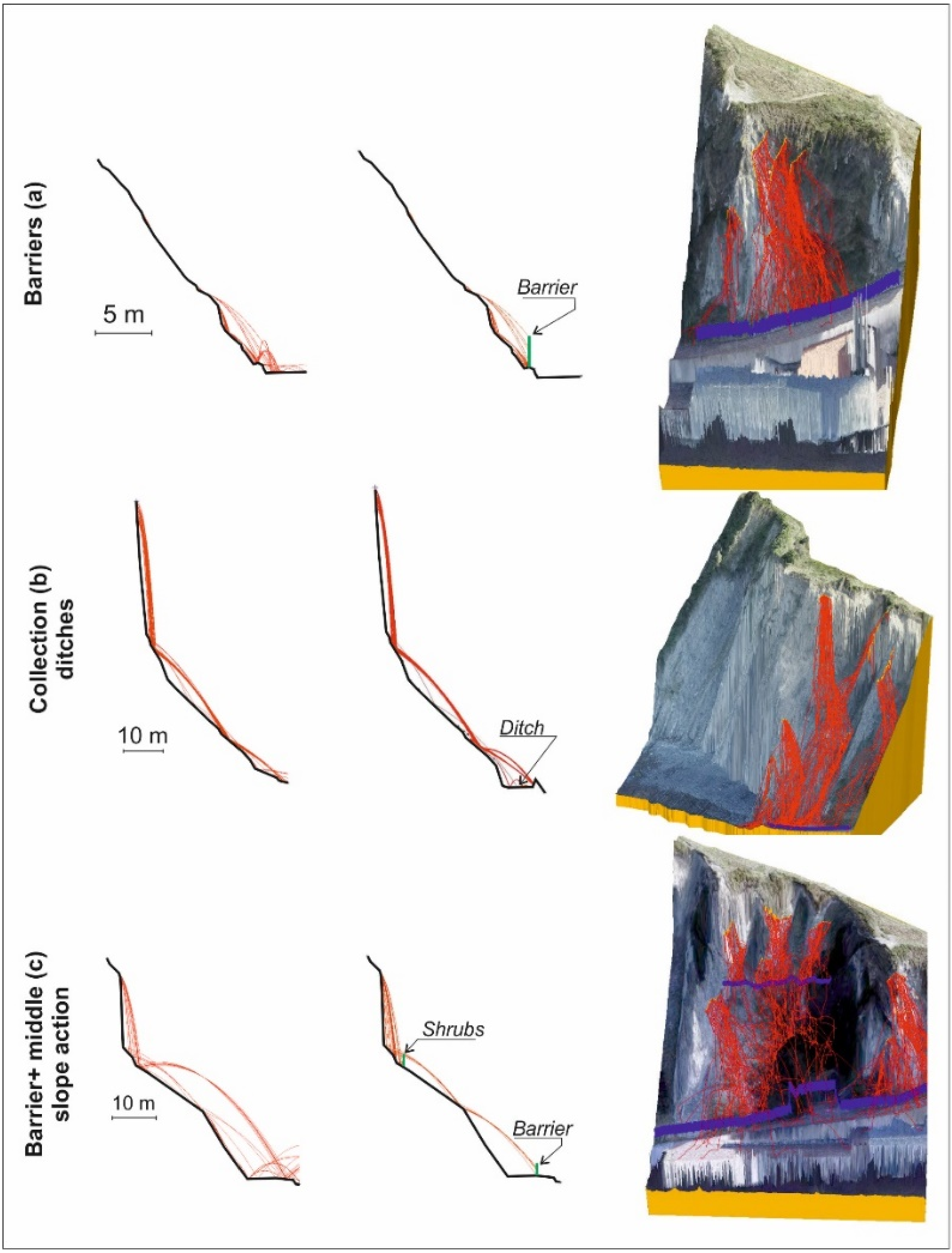


Fig. 8. Current status (left figures) and proposed mitigation actions in 2D (middle figures) and 3D (right figures). a) Rigid barrier; b) collection ditch; c) barrier and actions in the middle slope.

-Protection of the access area by means of barriers in the base or the middle of the slope. The installation of semi-rigid barriers similar to those already existing in zones E and F (Fig.6) is considered the most recommendable option. These are barriers built with wooden elements of 100 mm diameter, internally reinforced with corrugated steel bars of 10 mm diameter, which have proven to be efficient for blocks of up to 800 N, with impact energies of up to 5 kJ. In each specific zone, barriers of different heights were tested to analyze their capacity of fall interception with the 3D model (Fig.8a). In those stretches where high barriers (> 2 m) would be required, retention elements at different levels of the slope (middle slope actions) were considered to limit rebounds (Fig.8b). These actions may correspond to barriers similar to those previously described or local plantations of shrubs that may favor rock retention in a natural way. Finally, in stretches where the terrain profile allows it, the barriers were complemented with catch areas or benches at the base of the slope. The effectiveness of these last measures cannot be verified with the 3D model, since it does not allow modifications of the relief, so in this case 2D profiles extracted from the three-dimensional trajectories were considered (Fig.8c).

Informative and preventive measures at the beach area, beyond the general removing of loose materials on the cliffs. In this sense, local population is against taking engineered measures, a condition that is shared by the managers.

Modeling allows the delimitation of rockfall reach with their energy, enabling to establish the corresponding use recommendations. In our case, we define a maximum reach area strip, surrounded by a 2 m preventive zone (Fig.9). The 2 m preventive zone width corresponds to the grid cell size used in the modeling. This information is communicated to users by means of information panels, flyers, computer applications, warning signs and through maintenance personnel.

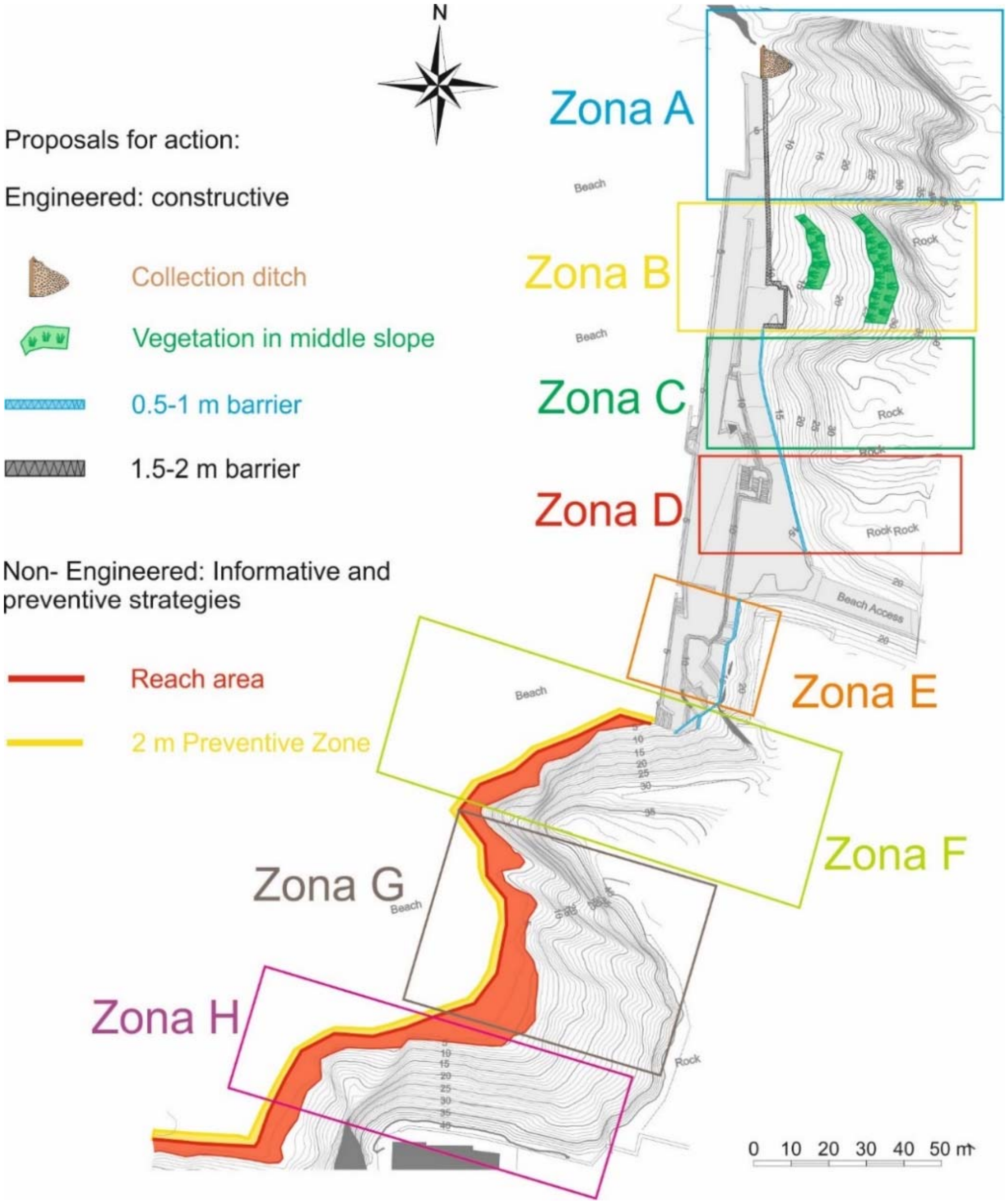


Fig. 9. Map of the recommended measures at Itzurun beach

5. Discussion

The approaches for studying rockfall events are included in three main categories (Shirzadi et al., 2012): empirical models based on relationships between topography and rockfall reach; GIS-based models handling large amounts of geospatial information linked to the development of rockfalls (Evans and Hungr, 1993; Guzzetti et al., 1999; Kaur et al., 2018; Reichenbach et al., 2018; Depountis et al., 2020); and process-based models describing the motion of falling rocks (Pfeiffer and Bowen, 1989; Kobayashi et al., 1990).

Our work deals with the characterization and management of rockfalls in coastal cliffs, where the source areas correspond to the rocky outcrops of the front of the cliffs. The delimited spatial reach of the processes, in a well-defined geomorphological element, facilitates both obtaining direct field measures and simulations using high-resolution digital terrain models. This leads us to use a process-based approach to determine the maximum reach and energy of the detached rock blocks. Direct information promotes an accurate recognition of the susceptibility of the environment from which to establish appropriate control and management measures.

Thus, 2-year field records completed with historical information allowed to approach the typology, frequency and entity of the rockfall events in a similar way to rockfall inventories considered in previous works (Bunce et al., 1997; Hungr et al., 1999; Volkwein et al., 2011). At the Itzurun beach, results show (Fig. 5) that the general frequency distribution of rockfall volumes follows a classical power law (Dussauge-Peisser et al., 2003; Hungr et al., 1999; Volkwein et al., 2011). By zones, however, the distribution corresponding to the major blocks (up to 100 N) deposited at the base of the slopes fits a normal density function (Fig. 6). These blocks are originated in the most competent layers of limestones and marls where joint families generate a relatively symmetrical distribution. Rockfall typologies correspond mainly to topplings, with a minor representation of rock plane and infinite slope instabilities.

Rockfall modeling is approached by 3D models. 3D numerical modeling allows including geometrical and dynamic effects of the 3D topography and taking into account the lateral dispersion generating 3D trajectories, overcoming the limitations of 2D models (Volkwein et al., 2011). In our work, a detailed digital terrain model obtained by UAV with a precision of 20 cm is included in RocPro3D software (RocPro3D, 2014). In any case, when changes in the topography are considered the 2D Rocfall software is used (RocScience, 2004).

The first main objective of the modeling effort is to establish the maximum reach and energy of falling blocks. With this aim, the block size considered for design in each differentiated zone corresponds to the 95% of the blocks distribution (as superior characteristic value, Bond and Harris, 2008), where information enough allows a statistical approach, or maximum-recorded sizes if not. Referring to the materials in the slope, 4 types of terrains with clearly differentiate mechanical response were considered. Results were ground-truthed with field observations. In any case, this item presents field of improvement, since the characteristic parameters of materials were obtained through adjustment, and additional experimental determinations and a more detailed characterization of the materials (i.e. based on rock mass classification in the case of rocky outcrops, Hoek, 1994; Morales et al., 2004) will enable us to verify and refine the results.

Once the susceptibility analysis is achieved, management and protection measures are proposed according with the reach and impact energies. In this sense, the information on boulder velocity, jump heights and spatial distribution is the basis for correct design and verification of protective measures (Volkwein et al., 2011). The main limitation in the design of these actions is the development of measures that are harmonious with the environment, avoiding the negative public perception that engineered works may bring (Touili et al., 2014; Ewalt Gray et al., 2017). For the Itzurun beach, as the maximum energy values computed where relative low, up to 12 kJ, protection measures in the access zones include 1–2 m barriers, if necessary combined with middle slope natural buffers, as rows of shrubs, and ditches. The effectiveness of those actions can be approached from guides for standardized barriers (i.e. Volkwein et al., 2019 for flexible systems). In any case, it is more appropriate to maintain unique protective elements, such as existing wooden barriers, whose effectiveness was verified after two events that took place in May and August 2020, adjusting the predicted in this work (Fig. 6a). For the beach sandy zones, at the request of population and managers, not engineered management actions were proposed, but information and warnings of susceptibility.

6. Conclusions

The management of cliffs that all along worldwide coasts join a high landscape and cultural value with a growing attraction of visitors requires the development of specific characterization strategies to assess their susceptibility to instabilities and implement friendly and minimally invasive management strategies to ensure safety.

In this context, this paper deals with the problematic associated with rockfalls in environments where the source areas correspond to the rocky outcrops of the front of the cliffs. In these cases, detailed both topographic information and direct field characterization of rockfall processes allow the development of detailed 3D models, from which to establish susceptibility analysis defining the maximum reach and energy of the detached blocks.

From this information, friendly management strategies may be proposed, having the following priority objectives: to be effective, to solve the problem; minimally invasive, to preserve the natural character of the environment; proportional, in accordance with the established safety objectives; and reversible, to guarantee the durability of the environment.

This comprehensive approach has been proved in the Basque Coast Geopark and can be useful in different spatially well-defined geomorphological environments, not necessarily coastal, with similar processes of instability, particularly in cliff areas enclosing widely visited environments.

Acknowledgements

This study has been carried out by the UPV/EHU Research Group IT-1029/16 (Government of the Basque Country) in the framework of the strategic project "Analysis of instabilities in coastal environments of the Basque Country" PES-18/97 (University of the Basque Country) and the collaboration of the Basque Coast Geopark (Geoparkea). Finally, the authors are grateful to the reviewers and the handling editor, for the valuable comments that highly improved the paper.

References

Abellán, A., Calvet, J., Vilaplana, J.M., Blanchard, J., 2010. Detection and spatial prediction of rockfalls by means of terrestrial laser scanner monitoring. Geomorphology 119: 162–171. https://doi.org/10.1016/j.geomorph.2010.03.016.

Agisoft, 2018. Agisoft metashape user manual: Professional edition, version 1.5. Agisoft LLC. https://www.agisoft.com/

Agliardi, F., Crosta, G.B., 2003. High resolution three-dimensional numerical modelling of rockfalls. International Journal of Rock Mecahnics & Mining Sciences 40, 455-471. https://doi.org/10.1016/S1365-1609(03)00021-2

Agliardi, F., Crosta, G.B., Frattini, P., 2009. Integrating rockfall risk assessment and countermeasure design by 3D modelling techniques. Natural Hazards and Earth System Sciences 9, 1059-1073. https://doi.org/10.5194/nhess-9-1059-2009

Alessio, P., Keller, E.A., 2020. Short-term patterns and processes of coastal Cliff erosion in Santa Barbara, California. Geomorphology 353, 106994. https://doi.org/10.1016/j.geomorph.2019.106994

Álvarez-Marrón, J., Hetzel, R., Niedermann, S., Menéndez, R., Marquínez, J., 2008. Origin, structure and exposure history of a wave-cut platform more than 1 Ma in age at the coast of northern Spain: A multiple cosmogenic nuclide approach. Geomorphology 93, 316–334. https://doi.org/10.1016/j.geomorph.2007.03.005.

Andrasanu, A., 2009. Geoeducation, geoparks and geoconservation. In: Proc. 8th European Geoparks Conference: New Challenges with Geoturism, Idanha-a-Nova, Portugal, p. 187.

Ansari, M.K., Ahmad, M., Singh, R., Singh, T.N., 2018. 2D and 3D rockfall hazard analysis and protection measures for Saptashrungi Gad Temple, Vani, Nashik, Maharashtra – A case study. J. Geol. Soc. India 91, 47–56. https://doi.org/10.1007/s12594-018-0819-8.

Arenillas, I., Molina, E., Ortiz, S., Schmitz, B., 2008. Foraminiferal and d13C isotopic event-stratigraphy across the Danian–Selandian transition at Zumaya (northern Spain): chronostratigraphic implications. Terra Nova 20, 38–44. https://doi.org/10.1111/j.1365-3121.2007.00784.x.

Arz, J.A., Canudo, J.I., Molina, E., 1992. Estudio comparativo del Maastrichtiense de Zumaya (Pirineos) y Agost (Béticas) basado en el análisis cuantitativo de los foraminíferos plantónicos. In: Actas III Congreso Geológico de España y VIII Congreso Latinoamericano de Geología, Salamanca, España. Tomo 1, pp. 487–491.

Asteriou, P., 2018. Effect of Impact Angle and Rotational Motion of Spherical Blocks on the Coefficients of Restitution for Rockfalls. Geotech. Geol. Eng. 37, 2523–2533. https://doi.org/10.1007/s10706-018-00774-0.

Baceta, J.I., Orue-Etxebarria, X., Apellaniz, E., Martin-Rubio, M., Bernaola, G., 2012. El Flysch del litoral Deba-Zumaia: una "ventana" a los secretos de nuestro pasado geológico. Servicio Editorial de la Universidad del País Vasco, Bilbao.

Barnolas, A., Pujalte, V. (Eds.), 2004. La Cordillera Pirenaica. In: Vera, J.A. (Ed.), Geología de España. SGE-IGME, Madrid, pp. 233–343.

Bernaola, G., Martín-Rubio, M., Baceta, J.I., 2009. New high resolution calcareous nannofossil analysis across the Danian/Selandian transition at the Zumaia section: comparison with South Tethys and Danish sections. Geol. Acta 7, 79-92. https://doi.org/10.1344/105.000000272.

Bilbao-Lasa, P., Jara-Muñoz, J., Pedoja, K., Álvarez, I., Aranburu, A., Iriarte, E., Galparsoro, I., 2020. Submerged Marine Terraces Identification and an Approach for Numerical Modeling the Sequence Formation in the Bay of Biscay (Northeastern Iberian Peninsula). Frontiers in Earth Science 8:47. https://doi.org/10.3389/feart.2020.00047

Bird, E., 2000. Coastal geomorphology: an introduction. John Wiley & Sons, New York.

Black, G.P., Gonggrijp, G.P., 1990. Fundamental thoughts on Earth-Science conservation. Jb. Geol. B.-A. 133, 655-657.

Boillot, G., Capdevila, R., 1977. The Pyrenees: Subduction and collision. Earth Planet. Sci. Lett. 35, 151-160. https://doi.org/10.1016/0012-821X(77)90038-3.

Bond, A., Harris, A., 2008. Decoding Eurocode 7. Taylor and Francis, London, pp. 263-304.

Brilha, J., 2002. Geoconservation and protected areas. Environ. Conserv. 29, 273–276. https://doi.org/10.1017/S0376892902000188.

Brilha, J., 2018. Geoheritage and Geoparks. In: Reynard, E., Brilha, J. (Eds.), Geoheritage: Assessment, Protection, and Management. Elsevier, Amsterdam, The Netherlands, pp. 323–335. https://doi.org/10.1016/B978-0-12-809531-7.00018-6.

Budetta, P., Santo, S., 1994. Morphostructural evolution and related kinematics of rockfalls in Campania (southern Italy): A case study. Eng. Geol. 36, 197–210. https://doi.org/10.1016/0013-7952(94)90004-3.

Bunce, C.M., Cruden, D.M., Morgenstern, N.R., 1997. Assessment of the hazard from rock fall on a highway. Can. Geotech. J. 34, 344-356. https://doi.org/10.1139/cgj-34-3-344

Canuti, P., Margottini, C., Fanti, R., Bromhead, E.N., 2009. Cultural heritage and landslides: Research for risk prevention and conservation. In: Sassa, K., Canuti, P. (Eds), Landslides – Disaster risk reduction. Springer, Berlin, Heidelberg, pp. 401–433. https://doi.org/10.1007/978-3-540-69970-5_22.

Chen, G., Zheng, L., Zhang, Y., Wu, J., 2013. Numerical Simulation in Rockfall Analysis: A Close Comparison of 2-D and 3-D DDA. Rock Mech. Rock. Eng. 46, 527-541. https://doi.org/10.1007/s00603-012-0360-9

Collins, B.D., Sitar, N., 2007. Processes of coastal bluff erosion in weakly lithified sands, Pacifica, California, USA. Geomorphology 97 (3–4), 483–501. https://doi.org710.1016/j.geomorph.2007.09.004

Crosta, G.B., Agliardi, F., 2003. A methodology for physically based rockfall hazard assessment. Natural Hazards and earth System Sciences 3, 407-422. https://doi.org/10.5194/nhess-3-407-2003

Crosta, G.B., Agliardi, F., 2004. Parametric evaluation of 3D dispersion of rockfall trajectories. Nat. Hazards Earth Syst. Sci. 4, 583–598. https://doi.org/10.5194/nhess-4-583-2004.

Crosta, G.B., Agliardi, F., Frattini, P., Lari, S., 2015. Key Issues in Rock Fall Modeling, Hazard and Risk Assessmnet for Rockfall Protection. Engineering Geology for Society and territory- Volume 2. https://doi.org/10.1007/978-3-319-09057-3_4

Depountis, N., Nikolakopoulos, K., Kavoura, K., Sabatakakis, N., 2020. Description of a GIS-based rockfall hazard assessment methodology and its application in mountainous sites. Bulletin of Engineering Geology and the Environment 79, 645-658. https://doi.org/10.1007/s10064-019-01590-3

Dorren, L.K.A., 2003. A review of rockfall mechanics and modelling approaches. Prog. Phys. Geogr. 27, 69–87. https://doi.org/10.1191/0309133303pp359ra.

Dorren, L.K.A., Domaa, U., Kronholm, K., Labiouse, V., 2013. Methods for predicting rockfall trajectories and run-out zones. In: Lambert, S., Nicot, F., (Eds.), Rockfall engineering. ISTE Ltd. / John Wiley & Sons Inc, London / Hoboken, pp. 143-173. https://doi.org/10.1002/9781118601532.ch5.

Duperret, A., Genter, A., Martinez, A., Mortimore, R.N., 2004. Coastal chalk cliff instability in NW France: role of lithology, fracture pattern and rainfall. Geological Society, London, Engineering Geology Special Publications 20 (1), 33–55. https://doi.org/10.1144/GSL.ENG.2004.020.01.03

Dussauge-Peisser, C., Grasso, C., Helmstetter, A., 2003. A statistical analysis of rockfall volume distributions: Implications for rockfall dynamics. J. Geophys. Res. Sol. Ea. 108, 1-11. https://doi.org/10.1029/2001JB000650

Emery, K.O., Kuhn, G.C., 1982. Sea cliffs: their processes, profiles, and classification. Geol. Soc. Am. Bull. 93, 644–654. https://doi.org/10.1130/0016-7606(1982)93<644:SCTPPA>2.0.CO;2.

Evans, S., Hungr, O., 1993. The assessment of rockfall hazard at the base of the talus slopes. Can. Geotech. J. 30, 620-636.

Ewalt Gray, J.M., O'Neill, K., Qiu, Z., 2017. Coastal residents' perceptions of the function of and relationship between engineered and natural infrastructure for coastal hazard mitigation. Ocean & Coastal Management 146, 144-156. https://doi.org/10.1016/j.ocecoaman.2017.07.005

Fanos, A.M., Pradhan, B., 2019. A novel rockfall hazard assessment using laser scanning data and 3D modelling in GIS. Catena 172, 435–450. https://doi.org/10.1016/j.catena.2018.09.012.

Feuillée, P., Rat, P., 1971. Structures et paléogéographies pyrénéo-cantabriques. In: Debyser, J., Le Pichon, X., Montardet, L. (Eds.), Histoire structural du Golfe de Gascogne, Tome 2. Publ. l'Inst. Français Pétrole, Coll. et Sémin., Technip, Paris, pp. 1–48.

Feurer, D., Vinatier, F., 2018. Joining multi-epoch archival aerial images in a single SfM block allows 3-D change detection with almost exclusively image information. ISPRS J. Photogramm. Remote Sens. 146, 495–506. https://doi.org/10.1016/j.isprsjprs.2018.10.016.

Fraternali, F., 2007. Free discontinuity finite element models in two-dimensions for in- plane crack problems. Theor. Appl. Fract. Mech. 47, 274–282. https://doi.org/10.1016/j.tafmec.2007.01.006.

Frattini, P., Crosta, G., Carrara, A., Agliardi, F., 2008. Assessment of rockfall susceptibility by integrating statistical and physically-based approaches. Geomorphology 94, 419–437. https://doi.org/10.1016/j.geomorph.2006.10.037.

Frattini, P., Crosta, G., Agliardi, F., 2012. Rockfall characterization and modeling. In: Clague, J.J., Stead, D. (Eds), Landslides: types, mechanisms and modeling. Cambridge University Press, Cambridge, pp. 267–281.

Galparsoro, I., Borja, A., Legorburu, I., Hernández, C., Chust, G., Liria, P., Uriarte, A., 2010. Morphological characteristics of the Basque continental shelf (Bay of Biscay, northern Spain); their implications for Integrated Coastal Zone Management. Geomorphology 118, 3-4, 314-329. https://doi.org/10.1016/j.geomorph.2010.01.012

Garrido-Carretero, M.S., de Lacy-Pérez de los Cobos, M.C., Borque-Arancón, M.J., Ruiz-Armenteros, A.M., Moreno-Guerrero, R., Gil-Cruz, A.J., 2019. Low-cost GNSS receiver in RTK positioning under the standard ISO-17123-8: A feasible option in geomatics. Measurement 137, 168-178. https://doi.org/10.1016/j.measurement.2019.01.045.

Genna, A., Capdeville, J-P., Dubreuilh, J., Mallet, C., 2005. Évolution récente et actuelle de la côte basque française (analyse et perspectives). C.R. Geosci. 337, 1474–1483. https://doi.org/10.1016/j.crte.2005.08.010.

Glade, T., 2003. Vulnerability assessment in landslide risk analysis. Die Erde 134, 121–138.

González-Amuchastegui, M.J., Serrano-Cañadas, E., Edeso- Fito, J.M., Meaza-Rodriguez, G., 2005. Cambios en el nivel del mar durante el Cuaternario y morfología litoral en la costa oriental cantábrica (País Vasco y Cantabria). In: Sanjaume, E., Mateu, J.F. (Eds.), Geomorfologia litoral i Quaternari, Libro Homenaje al Prof. V.M. Roselló i Verger. Publicaciones Universitat de València, Valencia, pp. 167-180.

Guo, Q., Wang, X., Zhang, H., Li, Z., Yang, S., 2009. Damage and conservation of the high cliff on the Northern area of Dunhuang Mogao Grottoes, China. Landslides 6, 89–100. https://doi.org/10.1007/s10346-009-0152-9.

Gutiérrez-Elorza, M., 2008. Geomorfología. Pearson/Prentice Hall, Madrid.

Guzzetti, F., Carrara, A., Cardinali, M., reichenbach, P., 1999. Landslide hazard evaluation: a review of current techniques and their application in a multi-scale study, Central Italy, Geomorphology 31, 181-216. https://doi.org/10.1016/S0169-555X(99)00078-1

Hampton, M.A., Griggs, G.B., 2004. Formation, Evolution, and Stability of Coastal Cliffs–Status and Trends. USGS Professional Paper 1693, 1-4.

Henriques, M.H., dos Reis, R.P., Brilha, J., Mota, T., 2011. Geoconservation as an emerging geoscience. Geoheritage 3, 117–128. https://doi.org/10.1007/s12371-011-0039-8.

Hernández-Gutiérrez, L.E., Santamarta, J.C. (Eds.), 2015. Ingeniería geológica en terrenos volcánicos: Métodos, técnicas y experiencias en las Islas Canarias. Ilustre Colegio Oficial de Geólogos. Madrid.

Hoek, E., 1994. Strength of rock and rock masses. ISRM News J. 2(2), 4–16.

Hungr, O., Evans, S., Hazzard, J., 1999. Magnitude and frequency of rockfalls and rock slides along the main transportation corridors of south-western British Columbia. Can. Geotech. J. 36, 224-238. https://doi.org/10.1139/t98-106

ICOMOS, 2003. Principios para el análisis, conservación y restauración de las estructuras del patrimonio arquitectónico. Victoria Falls, Zimbabwe.

Jiang, Z., Du, J., Rieck, C., Bück, A., Tsotsas, E., 2020. PTV experiments and DEM simulations of the coefficient of restitution for irregular particles impacting on horizontal substrates. Powder Technol. 360, 352–365. https://doi.org/10.1016/j.powtec.2019.10.072.

Jing, R., Gong, Z., Zhao, W., Pu, R., Deng, L., 2017. Above-bottom biomass retrieval of aquatic plants with regression models and SfM data acquired by a UAV platform – A case study in Wild Duck Lake Wetland, Beijing, China. ISPRS J. Photogramm. Remote Sens. 134, 122–134. https://doi.org/10.1016/j.isprsjprs.2017.11.002.

Kaur, H., Gupta, S., Parkash, S., Thapa., 2018. Application of geospatial technologies for multi-hazard mapping and characterization of associated risk at local scale. Ann GIS 24(1):33–46. https://doi.org/10.1080/19475683.2018.1424739

Keskin, I., 2013. Evaluation of rockfalls in an urban area: the case of Boğaziçi (Erzincan/Turkey). Environ. Earth Sci. 70, 1619–1628. https://doi.org/10.1007/s12665-013-2247-9.

Kim, K., Choi, J., Chung, J., Koo, G., Bae, I-H., Sohn, H., 2018. Structural displacement estimation through multi-rate fusion of accelerometer and RTK-GPS displacement and velocity measurements. Measurement 130, 223–235. https://doi.org/10.1016/j.measurement.2018.07.090.

Kirchner, K., Kubalíková, L., 2013. Relief assessment methodology with respect to geoheritage based on example of the Deblínská vrchovina highland. In: Fialová, J., Kubíčková, H. (Eds), Public recreation and landscape protection – with man hand in hand… Conference proceeding. Brno, pp. 131–141.

Kirchner, K., Kubalíková, L., 2015. Geomythology: A useful tool for geoconservation and geotourism purposes. In: Fialová J, Pernicová D, (Eds), Public recreation and landscape protection – with man hand in hand. Conference proceeding. Brno, pp. 68–74.

Kobayashi, Y., Harp, E., Kagawa, T., 1990. Simulation of Rockfalls triggered by earthquakes. Rock. Mech. Rock. Eng. Int. 19, 313-320. https://doi.org/10.1007/BF01020418

Kong, D., Wu, F., Saroglou, C., 2020. Automatic identification and characterization of discontinuities in rock masses from 3D point clouds. Eng. Geol. 265, 105442. https://doi.org/10.1016/j.enggeo.2019.105442.

Kubalíková, L., 2013. Geomorphosite assessment for geotourism purposes. Czech J. Tour. 2, 80–104. https://doi.org/10.2478/cjot-2013-0005.

Lambert, S. and Bourrier, F., 2013. Design of rockfall protection embankments: A review. Engineering Geology 154, 77-88. https://doi.org/10.1016/j.enggeo.2012.12.012

Lan, H., Martin, C.D., Lim, C.H., 2007. RockFall analyst: A GIS extension for three-dimensional and spatially distributed rockfall hazard modeling. Comput. Geosci. 33, 262–279. https://doi.org/10.1016/j.cageo.2006.05.013.

Li, L., Lan, H., 2015. Probabilistic modeling of rockfall trajectories: a review. Bull. Eng. Geol. Environ. 74, 1163–1176. https://doi.org/10.1007/s10064-015-0718-9.

Li, X., Dong, M., Jiang, D., Li, S., Shang, Y., 2020. The effect of surface roughness on normal restitution coefficient, adhesion force and friction coefficient of the particle-wall collision. Powder Technol. 362, 17–25. https://doi.org/10.1016/j.powtec.2019.11.120.

Lorentz, J., Plassiard, J.-P., Muquet, L., 2010. An innovative design process for rockfall embankments: application in the protection of a building at Val d'Isère. Proceed-ings of the 3rd Euro Mediterranean Symposium on Advances in Geomaterial sand Structures—AGS, Djerba, Tunisia, pp. 277–282.

Luckman, B.H., 2013. Processes, Transport, Deposition and Landforms: Rockfall. Treatise Geomorphology 7, 174–182. https://doi.org/10.1016/B978-0-12-374739-6.00162-7.

Margottini, C., Vilímek, V., 2014. The ICL Network on "Landslides and Cultural & Natural Heritage" (LACUNHEN). Lanslides 11, 933-938. https://doi.org/10.1007/s10346-014-0510-0.

Margottini, C., Gigli, G., Ruther, H., Spizzichino, D., 2016. Advances in sustainable conservation practices in rupestrian settlements inscribed in the UNESCO's World Heritage List. Procedia Earth Planet. Sci. 16, 52–60. https://doi.org/10.1016/j.proeps.2016.10.006.

Masuya, H., Amanuma, K., ishikawa, Y., Tsuji, T., 2009. Basic rockfall simulation with consideration of vegetation and application to protection measure. Natural Hazards and Earth System Sciences 9, 1835-1843. https://doi.org/10.5194/nhess-9-1835-2009.

Michoud, C., Derron, M.H., Horton, P., Jaboyedoff, M., Baillifard, F.J., Loye, A., Nicolet, P., Pedrazzini, A., Queyrel, A., 2012. Rockfall hazard and risk assessments along roads at a regional scale: example in Swiss Alps. Nat. Hazards Earth Syst. Sci. 12, 615–629. https://doi.org/10.5194/nhess-12-615-2012.

Morales, T., Uribe-Etxebarria, G., Uriarte, J.A., Fernández de Valderrama, I., 2004. Geomechanical characterisation of rock masses in Alpine regions: the Basque Arc (Basque-Cantabrian basin, Northern Spain). Engineering Geology 71, 343-362. https://doi.org/10.1016/S0013-7952(03)00160-1.

Morales, T., Uriarte, J.A., Damas, L., Antigüedad, I., 2018. Taludes inestables y patrimonio cultural: cómo y hasta dónde actuar. Una visión desde las Galerías Punta Begoña (Getxo, Bizkaia). In: Proc. of the VI Congreso del GEIIC, Vitoria-Gasteiz, pp. 426–433.

Orue-Etxebarria, X., Alegret, L., Apellaniz, E., Arenillas, I., Baceta, J.I., Bernaola, G., Caballero, F., Dinarès-Turell, J., Martín-Rubio, M., Molina, E., Ortíz, S., Pujalte, V., Schmitz, B., 2007. The Zumaia Section: a robust candidate for the placement of the Danian/Selandian and Selandian/Thanetian boundaries. In: International Workshop of the Paleocene Working Group. Zumaia. Volume of Abstracts, 33-35.

Panizza, M., 2001. Geomorphosites: Concepts, methods and example of geomorphological survey. Chinese Sci. Bull. 46, 4–5. https://doi.org/10.1007/BF03187227.

Pedoja, K., Husson, L., Johnson, M.E., Melnick, D., Witt, C., Pochat, S., Nexer, M., Delcaillau, B., Pinegina, T., Poprawski, Y., Authemayou, C., Elliot, M., Regard, V., Garestier, F., 2014. Coastal staircase sequences reflecting sea-level oscillations and tectonic uplift during the Quaternary and Neogene. Earth-Sci. Rev. 132, 13–38. https://doi.org/10.1016/j.earscirev.2014.01.007.

Pfeiffer, T.J., Bowen, T.D., 1989. Computer simulation of rockfalls. Bull. Assoc. Eng. Geol. 26, 135–146.

Pham, B.T., Pradhan, B., Tien Bui, D., Prakash, I., Dholakia, M.B., 2016. A comparative study of different machine learning methods for landslide susceptibility assessment: a case study of Uttarakhand area (India). Environ. Model. Softw. 84, 240–250. https://doi.org/10.1016/j.envsoft.2016.07.005.

Pierre, G., Lahousse, P., 2006. The role of groundwater in cliff instability: an example at Cape Blanc-Nez (Pas-de-Calais, France). Earth Surface Processes and Landforms: the Journal of the British Geomorphological Research. Group 31 (1), 31–45. https://doi.org/10.1002/esp.1229

Porter, N.J., Trenhaile, A.S., 2007. Short-term rock surface expansion and contraction in the intertidal zone. Earth Surface Processes and Landforms: the Journal of the British Geomorphological Research. Group 32 (9), 1379–1397. https://doi.org/10.1002/esp.1479

Pujalte, V., Baceta, J.I., Dinarès-Turell, J., Orue-Etxebarria, X., Parés, J.M., Payros, A., 1995. Biostratigraphic and magnetostratigraphic intercalibration of latest Cretaceous and Paleocene depositional sequences from the deep-water Basque basin, western Pyrenees, Spain. Earth Planet. Sci. Lett. 136, 17–30.

Ramírez del Pozo, J., 1973. Síntesis geológica de la provincia de Álava. Obra cultural de la Caja de ahorros de la Ciudad de Vitoria, Vitoria-Gasteiz.

Raquet, J., Lachapelle, G., 2001. RTK positioning with multiple reference stations. GPS World 12, 48–53.

Rebouças, G.F.S., Santos, I.F., Thomsen, J.J., 2019. Unilateral vibro-impact systems – Experimental observations against theoretical predictions based on the coefficient of restitution. J. Sound Vib. 440, 346–371. https://doi.org/10.1016/j.jsv.2018.10.037.

REDMAR, 2005. Resumen de parámetros relacionados con el nivel del amr y la marea que afectan a las condiciones de diseño y explotación portuaria. Puertos del Estado. https://www.puertos.es 19 pp.

Reichenbach, P., Rossi, M., Malamud, B.D., Mihir, M., Guzzetti, F., 2018. A review of statistically-based landslide susceptibility models. Earth. Sci. Rev. 180:60–91. https://doi.org/10.1016/j.earscirev.2018.03.001

RocPro3D, 2014. RocPro3D software. http://www.rocpro3d.com/rocpro3d_en.php

RocScience, 2004. RocFall software for risk analysis of falling rock on steep slope. RocScience's User's Guide. https://www.rocscience.com/software/rocfall

RocScience, 2013. Dips, Analyze orientation-based geological data. RocScience's User's Guide. https://www.rocscience.com/software/dips

Rosser, N.J., Petley, D.N., Lim, M., Dunning, S.A., Allison, R.J., 2005. Terrestrial laser scanning for monitoring the process of hard rock coastal cliff erosion. Q. J. Eng. Geol. Hidrogeol. 38, 363–375. http://dx.doi.org/10.1144/1470-9236/05-008.

Schmitz, B., Molina, E., Von Salis, K., 1998. The Zumaya section in Spain: a possible global stratotype section for the Selandian and Thanetian stages. Newsl. Stratigr. 36, 35–42. https://doi.org/10.1127/nos/36/1998/35.

Schmitz, B., Pujalte, V., Molina, E., Monechi, S., Orue-Etxebarria, X., Speijer, R.P., Alegret, L., Apellaniz, E., Arenillas, I., Aubry, M-P., Baceta, J.I., Berggren, W.A., Bernaola, G., Caballero, F., Clemmensen, A., Dinarès-Turell, J., Dupuis, Ch., Heilmann-Clausen, C., Hilario-Orús, A., Knox, R., Martín-Rubio, M., Ortiz, S., Payros, A., Petrizzo, M.R., Von Salis, K., Sprong, J., Steurbaut E., Thomsen, E., 2011. The Global Stratotype Sections and Points for the bases of the Selandian (Middle Paleocene) and Thanetian (Upper Paleocene) stages at Zumaia, Spain. Episodes 34, 220–243. https://doi.org/10.18814/epiiugs/2011/v34i4/002.

Shirzadi, A., Saro, L., Hyun Joo, O., Chapi, K., 2012. A GIS-based logistic regression model in rock-fall susceptibility mapping along a mountainous road: Salavat Abad case study, Kurdistan, Iran. Natural Hazards 64, 1639-1656. https://doi.org/10.1007/s11069-012-0321-3

Spadari, M., Kardani, M., De Carteret, R., Giacomini, A., Buzzi, O., Fityus, S., Sloan, S.W., 2013. Statistical evaluation of rockfall energy ranges for different geological setting of New South Wales, Australia. Eng. Geol. 158, 57–65. https://doi.org/10.1016/j.enggeo.2013.03.007.

Stoffel, M., Schneuwly, D.M., Bollschweiler, M., 2010. Assessing rockfall activity in mountain forest – implications for hazard assessment. In: Stoffel, M., Bollschweiler, M., Butler, D.R., Luckman, B. (Eds), Tree Rings and Natural Hazards: A state of the art (Advances in Global Change Research Book 41). Springer, Dordrecht, pp. 139–155. https://doi.org/10.1007/978-90-481-8736-2_13.

Sunamura, T., 1992. Geomorphology of Rocky Coasts. John Wiley and Sons, New York, NY.

Sunamura, T., 2015. Rocky coast processes: with special reference to the recession of soft rock cliffs. Proceeding of the japan Academy Ser B Physical and Biological Sciences. https://doi.org/10.2183/pjab.91.481

Tomás, R., Riquelme, A., Cano, M., Abellán, A., Jordá, L., 2016. Structure from Motion (SfM): una técnica fotogramétrica de bajo coste para la caracterización y monitoreo de macizos rocosos. In: 10º Simposio Nacional Ingeniería Geotécnica. A Coruña, pp. 209-216.

Touili, N., Baztan, J., Vanderlinden, J-P., Kane, I.O., Diaz-Simal, P., Pietrantoni, L., 2014. Public perception of engineering-based coastal flooding and erosion risk mitigation options: Lessons from three European coastal settings. Coastal Engineering 87, 205-209. https://doi.org/10.1016/j.coastaleng.2014.01.004

Trenhaile, A.S., 2010. The effect of Holocene changes in relative sea level on the morphology of rocky coasts. Geomorphology 114 (1–2), 30–41. https://doi.org/10.1016/j.geomorph. 2009.02.003

Valente, D.S.M., Momin, A., Grift, T., Hansen, A., 2020. Accuracy and precision evaluation of two low-cost RTK global navigation satellite systems. Comput. Electron. Agric. 168, 105142. https://doi.org/10.1016/j.compag.2019.105142.

Varnes, D.J., 1978. Slope movement types and processes, in Schuster, R.L., Krizek, R.J., eds. Landslides. Analysis and control: National Research Council, Washington, D.C. Transportation Research Board, Special Report 176, p. 11-33. http://onlinepubs.trb.org/Onlinepubs/sr/sr176/176-002.pdf

Volkwein, A., Schellenbger, K., Labiouse, V., Agliardi, F., Berger, F., Bourrier, F., Dorren, L.K.A., Jaboyedoff, M., 2011. Rockfall characterisation and structural protection- a review. Natural Hazards and Earth System Sciences 11, 2617-2651. https://doi.org/10.5194/nhess-11-2617-2011

Volkwein, A., Gerber, W., Klette, J., Spescha, G., 2019. Review of Approval of Flexible Rockfall Protection Systems According to ETAG 027. Geosciences 9: 49. https://doi.org/10.3390/geosciences9010049

Wang, L., Zheng, Z., Yu, Y., Liu, T., Zhang, Z., 2020. Determination of the energetic coefficient of restitution of maize grain based on laboratory experiments and DEM simulations. Powder Technol. 362, 645–658. https://doi.org/10.1016/j.powtec.2019.12.024.

Westoby, M.J., Brasington, J., Glasser, N.F., Hambrey, M.J., Reynolds, J.M., 2012. 'Structure-from-Motion' photogrammetry: A low-cost, effective tool for geoscience applications. Geomorphology 179, 300–314. https://doi.org/10.1016/j.geomorph.2012.08.021.

Wimbledon, W.A.P., Smith-Meyer, S., 2012. Geoheritage in Europe and its conservation. ProGEO, Oslo.

Wu, M., Liu, W., Wu, R., Zhang, X., 2019. Tightly combined GPS/Galileo RTK for short and long baselines: Model and performance analysis. Adv. Space Res. 63, 2003–2020. https://doi.org/10.1016/j.asr.2018.12.008.

Young, A.P., Guza, R.T., O'Reilly, W.C., Flick, R.E., Gutierrez, R., 2011. Short-term retreat statistics of a slowly eroding coastal cliff. Nat. Hazards Earth Syst. Sci. 11 (1), 205–217. https://nhess.copernicus.org/articles/11/205/2011/

Young, A.P., 2018. Decadal-scale coastal cliff retreat in southern and central California. Geomorphology 300, 164–175. https://doi.org/10.1016/j.geomorph.2017.10.010.

Zhang, P., Du, K., Tannant, D.D., Zhu, H., Zheng, W., 2018. Automated method for extracting and analysing the rock discontinuities from point clouds based on digital surface model of rock mass. Eng. Geol. 239, 109–118. https://doi.org/10.1016/j.enggeo.2018.03.020.

Zhang, Z., Luo, J., Chen, B., 2020. Spatially explicit quantification of total soil erosion by RTK GPS in win and water eroded croplands. Sci. Total Environ. 702, 134716. https://doi.org/10.1016/j.scitotenv.2019.134716

4.2. Capítulo II: Modelización de caída de rocas en los acantilados carbonatados "tipo flysch" de la playa de Atxabiribil (Sopela, Bizkaia): análisis tridimensional. Modeling of rockfall in the carbonate flysch cliffs of Atxabiribil beach (Sopela, Bizkaia): three-dimensional analysis

Acantilados del sector central de la playa de Atxabiribil (Sopela)

Jon Ander Clemente Momoitio, Jesus Ángel Uriarte Goti, Arturo Apraiz Atucha, Tomás Morales Juberías

Revista de la Sociedad Geológica de España

Volume 34 (2): 60-70. Diciembre de 2021

Abstract

Coastal cliffs attract millions of people every year for their landscape, natural and recreational value. However, these spaces develop instability processes that condition the practice of users, as well as their safety. For this reason, there is a need to develop detailed studies of instabilities, which allow the development of specific actions to ensure the safety and preserve the nature of these environments. The study carried out on Atxabiribil beach (Sopela, Bizkaia) seeks to understand the dynamics of rockfall on coastal cliffs and to develop three-dimensional models that reflect the observed reality. The modeling allows the simulation of individual rockfall trajectories, their lateral evolution, energy and reach, as well as detailed diagrams. This study allows advancing proposals based on informative measures and specific warnings with the delimitation of areas of greater process activity, seeking safety while the naturalness of the environment is maintained, avoiding constructive interventions.

Keywords: coastal cliffs, rockfalls, three-dimensional analysis.

Resumen

Los acantilados costeros atraen a millones de personas cada año por su valor paisajístico, natural y recreativo. Sin embargo, estos espacios desarrollan procesos de inestabilidad que condicionan el uso de los visitantes, así como su seguridad. Por esta razón, existe la necesidad de elaborar estudios detallados de inestabilidades, que permitan desarrollar actuaciones específicas que garanticen la seguridad y conserven la naturaleza de estos entornos. El estudio realizado en la playa de Atxabiribil (Sopela, Bizkaia) busca conocer las dinámicas de caída de rocas en los acantilados costeros y desarrollar modelos tridimensionales que reflejen la realidad observada. La modelización permite simular trayectorias individuales de caída de rocas, su evolución lateral, energía y alcance, así como realizar diagramas detallados. Este estudio permite avanzar propuestas basadas en medidas informativas y advertencias específicas con la delimitación de

áreas de mayor actividad de procesos, buscando la seguridad mientras la naturalidad del entorno se mantiene, evitando las intervenciones constructivas.

Palabras clave: acantilados costeros, caída de rocas, análisis tridimensional.

Introducción

Las regiones costeras son la residencia de más de 1.200 millones de personas a lo largo del mundo (Tonmoy et al., 2018). De estos espacios, se estima que entre el 52 y el 80% están limitados por acantilados costeros (Emery y Kuhn, 1982; Young y Carilli, 2019) que pueden contactar directamente con el mar, y evolucionar hacia rasas mareales o playas.

Estos espacios son de uso continuo, tanto por parte de la población local, como por su uso estival y turístico. En este sentido, a lo largo de las últimas décadas, han sufrido el desarrollo, a veces incontrolado, del urbanismo, con la invasión de espacios y la degradación del paisaje natural.

Por otra parte, estos espacios destacan por una alta dinámica litoral, en la que se incluyen procesos de inestabilidad, como la caída de rocas, que es un proceso de alta recurrencia y complejidad, resultado de factores geológicos y meteorológicos, que dan lugar a una gran variabilidad de dinámicas. En este contexto, la caída de rocas destaca como un proceso que se registra prácticamente en la totalidad de costas con afloramientos rocosos.

La Costa Vasca, en la que se desarrolla el estudio, se extiende a lo largo de 176 kilómetros. En ella, una parte importante de los acantilados costeros se desarrolla en alternancias sedimentarias de materiales carbonatados y siliciclásticos tipo flysch. En zonas protegidas se desarrollan playas, limitadas hacia el continente por acantilados que llegan a alcanzar alturas de 30 a 60 metros, en las que se registran continuos procesos de inestabilidad, especialmente caídas de rocas, particularmente peligrosas para las personas en verano. Ejemplos de playas con estas características son la playa de Itzurun en Gipuzkoa (Morales et al., 2021), y Atxabiribil, Barrika y Muriola en la costa de Uribe.

En este contexto, el objetivo del presente trabajo es plantear un estudio de detalle de los acantilados de la playa de Atxabiribil, que fueron modificados en los años 80 a 90, con la eliminación de parte de los resaltes naturales al considerar que hacían peligrar la seguridad de los usuarios. Esta actuación generó en su momento una notable controversia. En la actualidad, la zona se encuentra protegida como zona de especial protección y mejora ambiental por el Plan Territorial Sectorial de Protección y Ordenación del Litoral de la Comunidad Autónoma del País Vasco (CAPV), por lo que las actuaciones constructivas no están recomendadas y, dado que los acantilados están en contacto directo con la playa, las actuaciones de prevención, señalización e información adquieren un carácter prioritario (Morales et al., 2021). Para el desarrollo de las mismas, es necesario conocer el origen, evolución y desarrollo de procesos gravitacionales en los taludes actuales. Para ello se genera un Modelo Digital del Terreno y una cartografía de detalle, se caracterizan litológicamente los materiales en campo y laboratorio, se estudia la tipología de roturas, frecuencia y entidad de las mismas, y se desarrollan modelizaciones 3D que permiten el análisis tridimensional de la caída de rocas sobre la playa.

Contexto geográfico y geológico

La playa de Atxabiribil, con una longitud próxima a los 800 metros, forma parte de la conocida costa de Uribe en el litoral de Bizkaia (Fig. 1). La costa de Uribe tiene una longitud total de 13 kilómetros, desde el municipio de Getxo hasta Górliz, como límite septentrional. Todo el sector costero está reconocido geológicamente como Lugar de Interés Geológico (LIG CV008), principalmente por su valor geomorfológico, con un litoral acantilado prácticamente constante, playas de arena en entrantes protegidos, y el estuario del río Butroe. Sopela, municipio en el que se localiza la playa de Atxabiribil, recibe en los meses estivales una de las mayores afluencias de visitantes de todo el litoral de la comarca.

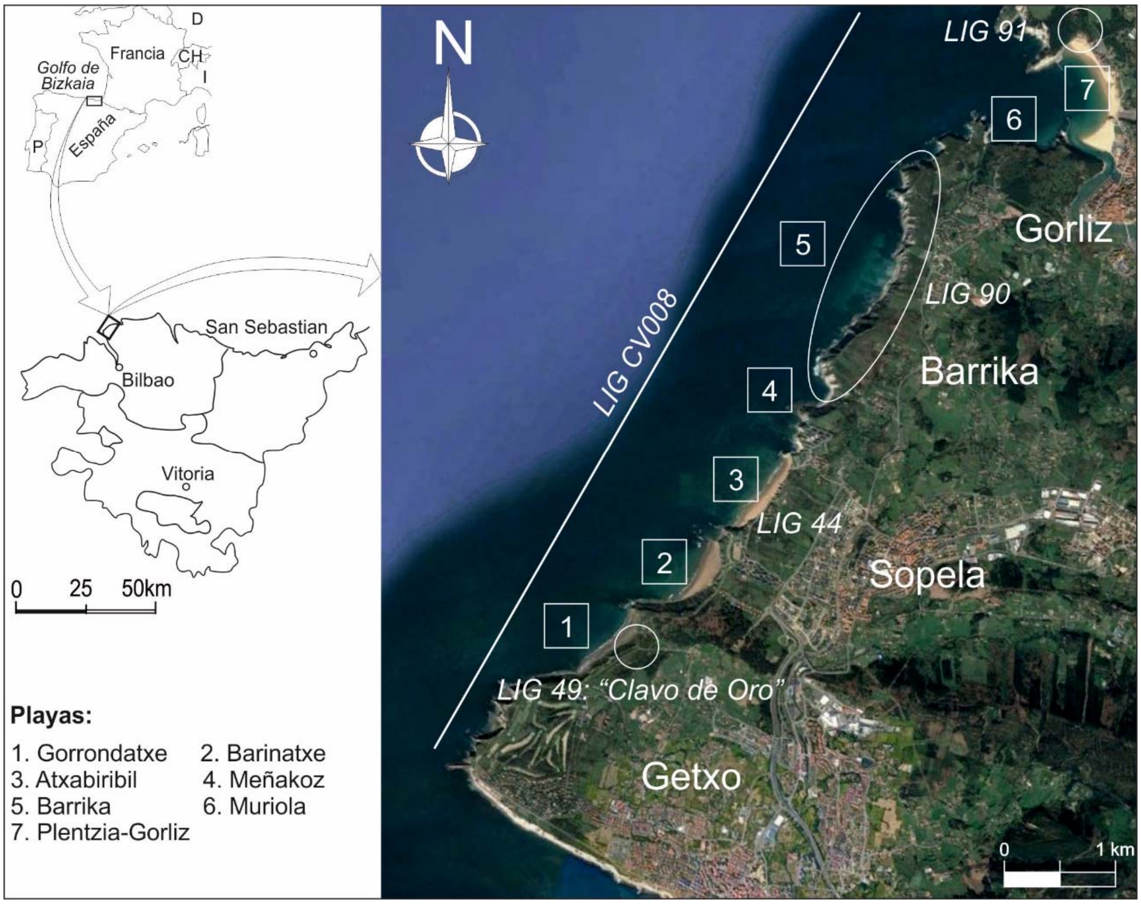


Fig. 1. Contexto geográfico, playas y Lugares de Interés Geológico (LIG) de la costa de Uribe. LIGS: CV008, Costa de Uribe; 44: Límite K/T Sopela (K/Pg en la actualidad); 49: Ypresiense-Luteciense de Gorrondatxe (GSSP); 90: Paleorrasa de Barrika; 91: Dunas fósiles de Astondo.

Desde un punto de vista geológico, el área de estudio se encuentra en la denominada Cuenca Vasco-Cantábrica, y más concretamente en el flanco noreste del Sinclinorio de Bizkaia (Fig. 2), dentro del Arco Vasco (Feuillé y Rat, 1971; Ramírez del Pozo, 1973). La evolución tectosedimentaria de esta cuenca es compleja, y comienza con una fase extensiva desarrollada durante el Mesozoico, particularmente durante el Cretácico, con una tasa de subsidencia elevada que dio lugar a una acumulación de materiales de gran potencia. Esta sedimentación se desarrolló en un fondo de cuenca (1000-1500 m) (Pujalte et al., 1998) en el que alternan series continuas de pares marga-caliza, zonas dominantemente margosas y eventos turbidíticos carbonatados eventuales procedentes del continente, en función de los ciclos de Milankovitch (Dinarès-Turell et al., 2013; Batenburg et al., 2014).

Posteriormente a la etapa extensiva, en la Cuenca Vasco-Cantábrica se desarrolló un gran evento compresivo durante la Orogenia Alpina, que elevó los materiales de fondo de cuenca previamente mencionados plegándolos. En este contexto, se desarrolló un sistema de fallas inversas subparalelas a la estratificación (70/210), que definen un movimiento cabalgante general hacia el norte, que se reconocen también en la playa de Atxabiribil (Fig. 2).

En cuanto a las litologías que afloran en los acantilados que bordean la playa de Atxabiribil, los materiales predominantes son sucesiones de pares de margas y margocalizas grises depositadas en un fondo de cuenca en el Maastrichtiense inferior (Álvarez-Llano et al., 2006), que son el material más antiguo del área de estudio. Para el mismo periodo geológico, destaca un afloramiento de aproximadamente 20 metros de margas y margocalizas grises y rojas del Maastrichtiense superior, depositados en un ambiente similar al anterior, que representan el último episodio sedimentario previo al límite con el Cenozoico (Iridoy et al., 2010; Dinarès-Turell et al., 2013). El límite Cretácico-Paleógeno (K/Pg) ha sido definido en la playa de Atxabiribil (LIG 44), y contiene un nivel rico en iridio con origen en el impacto meteorítico de hace 65 millones de años, que marca un cambio en el contenido de foraminíferos en ambos lados del citado límite (Lamolda et al., 1983). En concreto, la unidad inferior al límite es la definida como una alternancia de margas y margocalizas grises y rojas, que progresivamente desarrollan menor cantidad de estratos margocalizos, con un nivel margoso de color rojo en los últimos metros (Dinarès-Turell et al., 2013). La unidad suprayacente está formada por las calizas rosas del Daniense (Apellániz et al., 1983), que está constituida por calizas pelágicas de colores rosados y grises. Este sector es particularmente accesible desde que en el año 2008 y en aplicación de la Ley de Costas (Ley 22/1988, de 28 de julio) se derribaron los locales comerciales construidos en la zona. Por último, el material más joven, del Eoceno, aflora de forma discordante al noreste del área de estudio, en relación al contacto mecánico en una zona altamente tectonizada por la Orogenia Alpina. Se trata de una alternancia de margas y margocalizas, similar a las descritas para el Cretácico, pero que destacan por una mayor presencia de eventos turbidíticos y, como se ha indicado, por una mayor deformación tectónica, que da lugar a pliegues, estructuras de cizalla e incluso inversión tectónica (Rodríguez et al., 2008). De esta forma, el sistema de fallas inversas dispone, en este sector norte, los materiales del Maastrichtiense por encima de los materiales Eocenos.

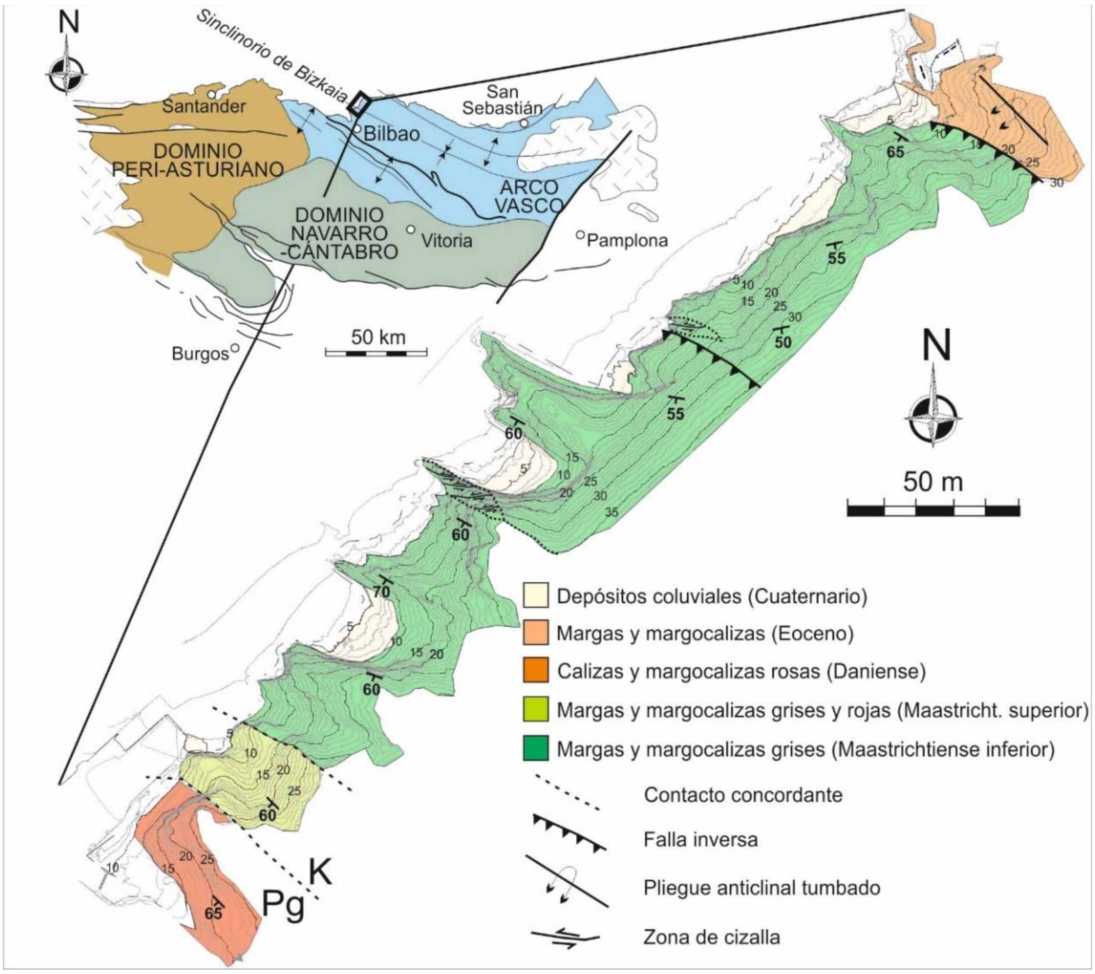


Fig. 2. Contexto geológico regional del área de estudio y de las estructuras principales de la Cuenca Vasco-Cantábrica (modificado de Feuillé y Rat, 1971). A la derecha se indica el mapa geológico del área de la playa de Atxabiribil.

Metodología

Información geográfica de detalle

La primera fase del trabajo ha consistido en la obtención de un Modelo Digital del Terreno, generado a partir de una nube de puntos tridimensional de detalle. Para ello, el área de estudio ha sido digitalizada mediante un equipo de Láser Escáner Terrestre (TLS) modelo FARO Focus 3D 330. Las nubes de puntos generadas mediante el TLS se utilizan en numerosas aplicaciones (Li et al., 2020), entre las que destacan la reconstrucción tridimensional de modelos (Dong et al., 2020) y la gestión del patrimonio de monumentos históricos construidos (Margottini y Spizzichino, 2014; Margottini et al., 2016; Spizzichino et al., 2019). Es fundamental que la información generada a partir del TLS en el campo, y que se establece con un sistema de coordenadas específico del área de estudio, sea convertida a un sistema de georreferenciación estándar, con el fin de facilitar no solo la combinación de esta información con documentos previamente generados, sino para facilitar la estandarización de todos los datos en un sistema común (Fan et al., 2015; Pandzic et al., 2017).

A partir de esta información, se obtiene una topografía de detalle, con una equidistancia entre curvas de nivel de 20 cm, que sirve de base para el trabajo de campo, y la nube de puntos previamente mencionada, que es utilizada para la modelización (Morales et al., 2021). En este sentido, se ha combinado la información generada con ortofotografías descargadas desde la Infraestructura de Datos Espaciales GeoEuskadi (https://www.geo.euskadi.eus/s69-15375/es/). El conjunto de la información se ha georreferenciado mediante la herramienta SIG (Sistemas de Información Geográfica) QGIS 3.8.

Caracterización geomecánica

La caracterización geomecánica de los materiales de los acantilados, se ha realizado mediante el índice de calidad RMR (Rock Mass Rating) de Bieniawski, 1989. Este índice incluye 5 parámetros de partida: resistencia a compresión simple de la roca, que obtenemos en campo mediante el Martillo de Schmidt (Fig. 3A); el valor de RQD (Rock Quality Designation) de Deere et al., 1967, que obtenemos a partir del número de juntas, que en nuestro caso corresponden al sistema de diaclasas y la estratificación, por metro cúbico (Jv); espaciado de las discontinuidades; estado/meteorización y presencia de agua. Además de estos parámetros se determina el grado de alterabilidad de los materiales menos resistentes de los acantilados mediante el Slake Durability Test (Fig. 3B). La resistencia a compresión simple de los materiales competentes se verifica en laboratorio mediante el ensayo de carga puntual (Fig. 3C). Finalmente, se realizan ensayos de inclinación o Tilt Test para determinar el ángulo de rozamiento residual de las juntas del macizo (Fig. 3D) y la rugosidad de las juntas o JRC (Joint Roughness Coefficient) mediante un perfilómetro de contacto.

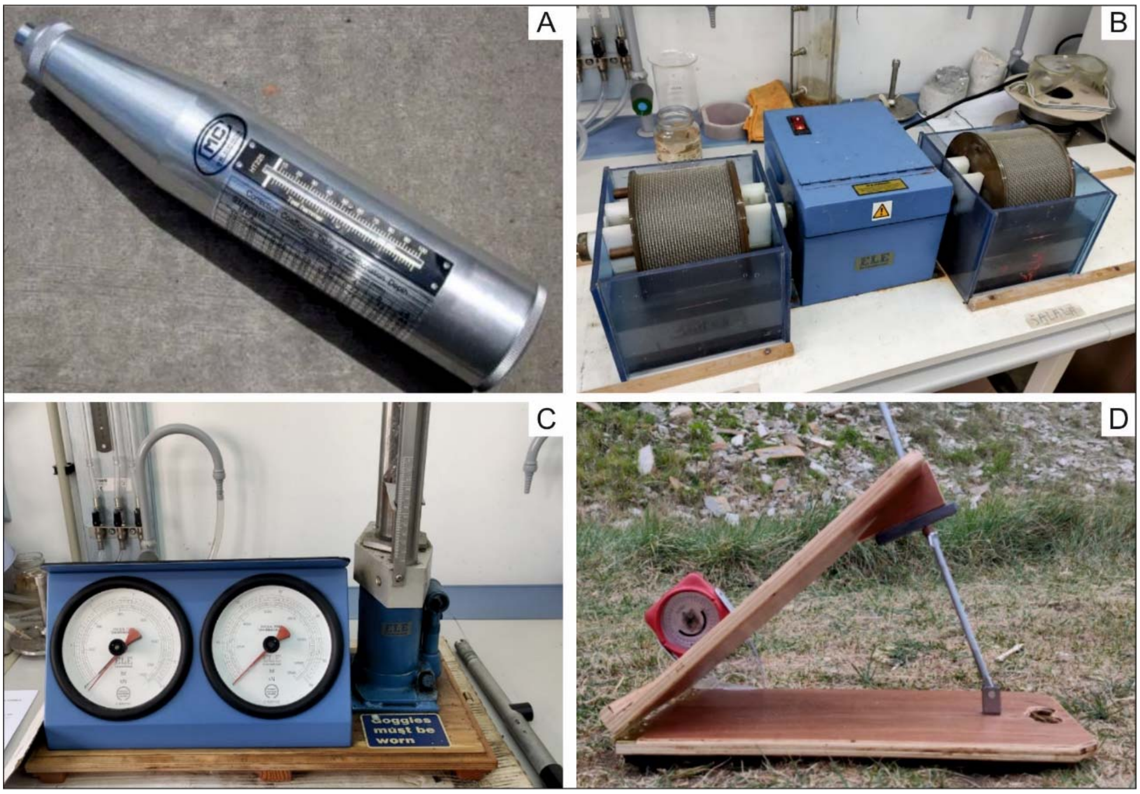


Fig. 3. Equipos utilizados para la caracterización de parámetros resistentes de los materiales. A) Martillo de Schmidt. B) Slake Durability test. C) Carga puntual. D) Tilt test.

Análisis de inestabilidades

El trabajo de campo se completa con el reconocimiento general de inestabilidades del área de estudio. La orientación, continuidad y desarrollo de las distintas familias de discontinuidad en los acantilados determina los procesos de inestabilidad, que son a su vez los precursores de las caídas de rocas.

Con el objetivo de desarrollar un análisis geométrico de los procesos potenciales de inestabilidad se han realizado proyecciones estereográficas sobre falsilla de Wulff mediante el programa Dips.v.6.0. de RocScience (RocScience, 2013). Este programa permite sintetizar la información de medida de planos recogida en el campo y realizar análisis cinemáticos para cada posible proceso de inestabilidad.

Los resultados obtenidos son contrastados con observaciones de campo, realizadas mediante revisiones periódicas en la zona durante los 3 años de duración de esta investigación, y una vez establecidos los procesos de caída de roca, se identifican las áreas fuente más activas, zonas de acumulación de bloques desprendidos, alcance desde el pie del talud y posible trayectoria. Esta información se recoge en la cartografía de detalle y posteriormente se compara con las modelizaciones. Junto con la dinámica del proceso, se caracteriza la morfología, dimensiones y peso de las rocas desprendidas mediante dinamómetros, lo que permite realizar simulaciones realistas del entorno.

Modelización

La modelización se realiza mediante el software RocPro3D (RocPro3D, 2014), que permite analizar la dinámica de caída de rocas en tres dimensiones. El primer paso es obtener, mediante triangulación, una malla tridimensional sobre la que simular los procesos considerados a partir de la nube de puntos previamente generada. Sobre esta malla se definen los distintos materiales identificados en el área de estudio. En nuestro caso se diferencian básicamente: zonas de afloramiento rocoso, zonas de vegetación, de playa y construidas. Cada uno de estos terrenos condiciona, mediante una serie de parámetros característicos, la evolución de la caída de rocas en función de la energía que retiene el terreno en los impactos, principalmente mediante los coeficientes de restitución normal (Rn), tangencial (Rt) y ángulo de rozamiento (⍰) (Pfeiffer y Bowen, 1989).

Sus resultados permiten identificar las zonas donde la caída de rocas alcanza una mayor energía, altura y velocidad, que resulta fundamental a la hora de elaborar propuestas de gestión preventivas e informativas, que son las recomendadas en la playa de Atxabiribil.

Resultados

<u>Sectorización del acantilado</u>

Teniendo como punto de partida la caracterización geomecánica del acantilado, se diferencian a lo largo de la playa 3 sectores en función de: la disposición general de los materiales respecto al talud del acantilado, el comportamiento frente a la erosión, la tipología de roturas dominantes y los usos de la playa (Fig. 4A, B). El primer sector, de menor calidad general del macizo (RMR:53), se desarrolla en el acceso norte de la playa y destaca por un mayor desarrollo de la fracturación, con una orientación general de la estratificación hacia el interior del acantilado. En el sector central de la playa el macizo es de mayor calidad (RMR:65), con una notable continuidad de la estratificación y dominio de los materiales más competentes, lo que favorece el desarrollo de un saliente en el acantilado; a diferencia del sector previo, la estratificación se dispone perpendicularmente a la línea de costa. Por último, el tercer sector, de calidad intermedia (RMR:58), se desarrolla en la zona de acceso sur a la playa; los estratos presentan también una marcada continuidad, y al igual que en el sector central se disponen perpendicularmente a la línea de costa.

Es importante añadir que en el sector 2 de la playa se instaló un muro de hormigón prácticamente continuo, con el objetivo de proteger el saliente del efecto del oleaje, lo que evita que la dinámica erosiva de la zona sea natural (Fig. 4C: cortesía de Javier Elorza).

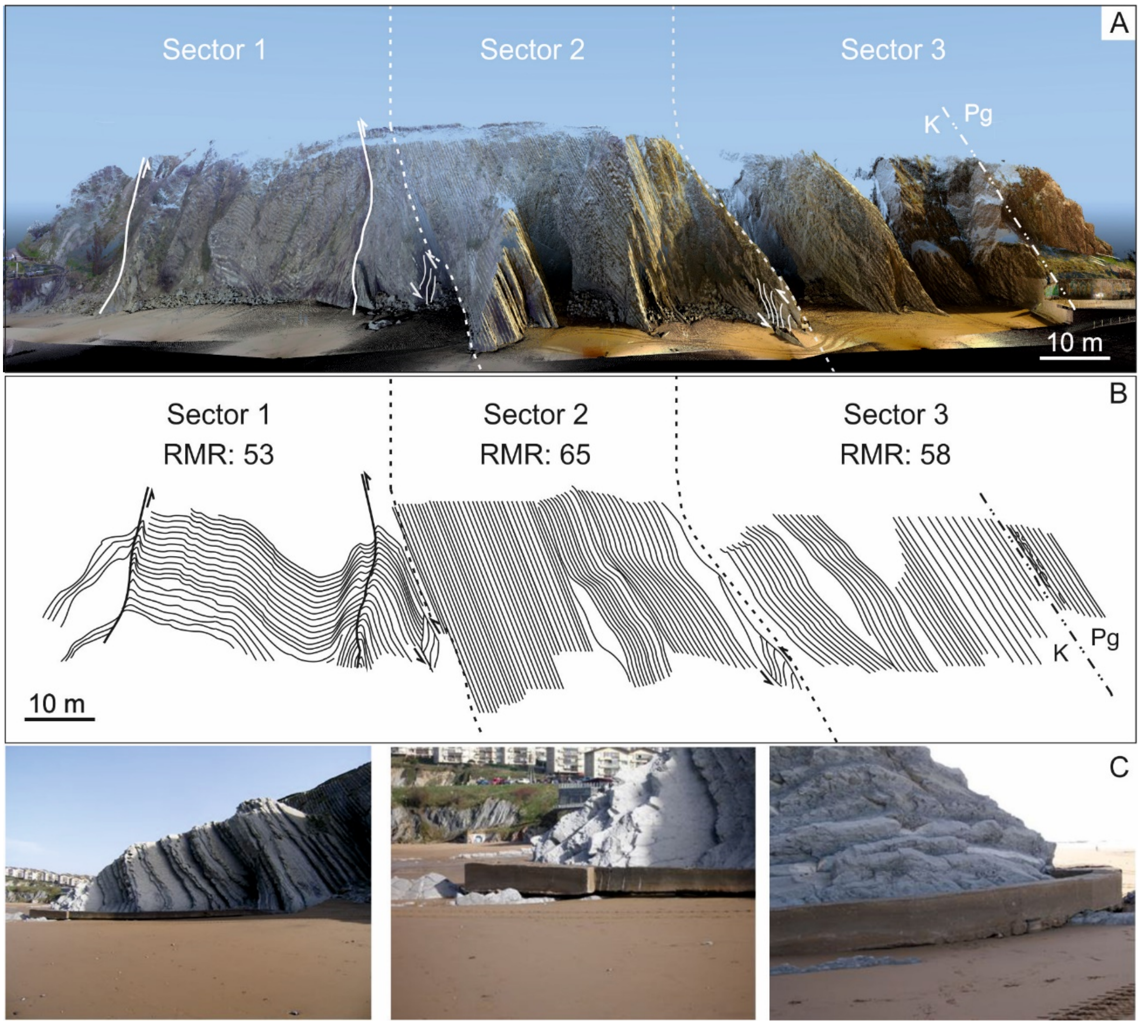


Fig. 4. A) Nube de puntos y sectorización de la playa de Atxabiribil. B) Disposición de materiales, estructuras tectónicas principales y valores de Rock Mass Rating (RMR) por sectores. C) Fotografías de la instalación del muro de hormigón en el sector 2, año 2008 (cortesía de Javier Elorza).

En lo que se refiere a las determinaciones de parámetros resistentes, los ensayos de campo y laboratorio se han centrado en los materiales del Maastrichtiense inferior y superior, que abarcan la mayor parte del área de estudio.

Para los materiales más competentes (margocalizas), se ha desarrollado una comparativa entre los valores de resistencia a compresión simple obtenidos en el campo mediante el martillo de

Schmidt y los del ensayo de carga puntual Point Load de laboratorio (Fig. 5A). Ambos valores muestran una clara correlación y varían entre 75 y 180 MPa, lo que equivale a una roca muy resistente (100-250 MPa).

Respecto de los materiales menos competentes (margas), los ensayos de durabilidad (Slake Durability Test) han permitido calcular su pérdida de peso después de 3 ciclos del ensayo. Esta pérdida supone únicamente un 2% del material, con una evolución muy similar en ambos tambores (Fig. 5B), lo que permite identificarlos como muy poco alterables. Destacar que este ensayo se desarrolla en ciclos de 10 minutos y caracteriza una degradación de naturaleza fundamentalmente física. No tiene en cuenta procesos de evolución más lenta y compleja, con componentes químicos y biológicos.

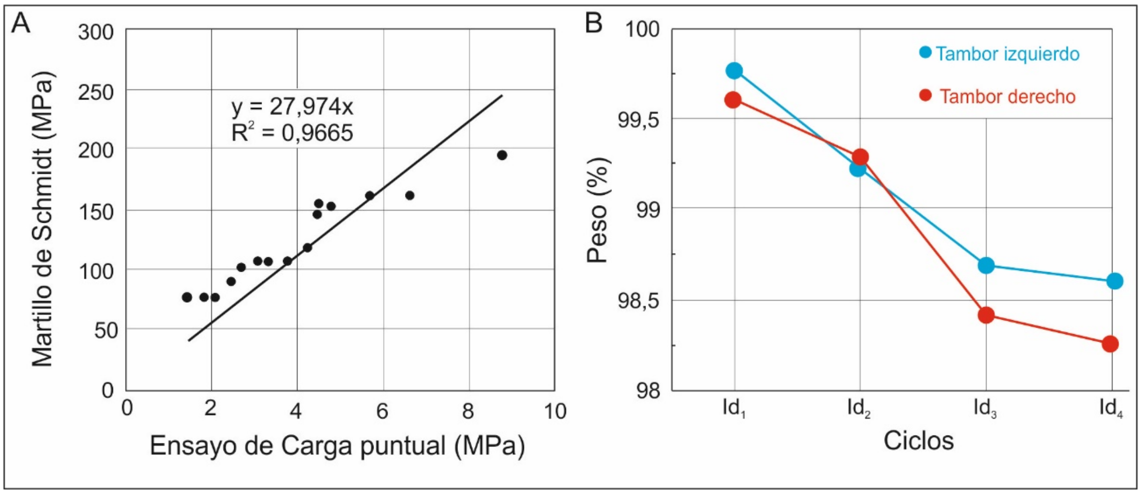


Fig. 5. Resultados gráficos de los ensayos de caracterización de materiales. A) Comparación entre los valores de resistencia a compresión simple obtenidos a partir del ensayo de carga puntual y esclerómetro o martillo de Schmidt. B) Pérdida de porcentaje de peso mediante slake durability test.

Tipología y caracterización de inestabilidades

En cuanto a la tipología de inestabilidades, la distinta orientación de materiales por sectores indicada en el apartado previo, da lugar a formas de rotura diferenciadas entre el sector 1 y los sectores 2 y 3.

En el sector 1, el talud principal tiene una orientación 80/285, y la estratificación presenta una orientación media (60/150), lo que dispone los estratos hacia el interior del acantilado, de forma general, como se ha indicado anteriormente. La labor erosiva del oleaje y las mareas favorece su descalce, dando lugar a movimientos rotacionales de bloques individuales (single block toppling, Alejano et al., 2010) que se desprenden de la masa rocosa, y más complejos, que involucran un volumen mayor de materiales, tienen una cierta componente de flexión y permanecen en gran medida unidos al macizo (flexural toppling), como el que se observa en la figura 6A.

En los sectores 2 y 3, se identifican tres familias de discontinuidad principales relativamente constantes. Destaca una estratificación muy continua (S0: 60/210), oblicua al acantilado (con ángulos próximos a 90º), y dos familias de juntas con orientaciones: 75/305 (J1) y 30/030(J2). En estos sectores, además del talud principal (70/295), la erosión diferencial da lugar a dos taludes adicionales enfrentados (Fig. 6B), uno sobre el techo de los estratos (talud anverso: 70/210) y otro a su base (talud reverso: 65/050). La interacción de estas tres familias da lugar a distintos procesos de inestabilidad, identificados tanto en campo como en las proyecciones estereográficas. En el talud principal, la estratificación (S0) y la junta J2 dibujan claras morfologías en cuña, limitadas hacia el interior por la junta J1, próxima a la vertical (Fig 6B, C).

En todo caso, dada la escasa inclinación de la línea de intersección entre los planos S0 y J2, no se registran deslizamientos de cuñas de tamaño reseñable. Sin embargo, dado que se trata de una alternancia de niveles decimétricos de materiales, las roturas, limitadas por los planos citados, se desarrollan como desprendimientos de bloques individuales, que en su conjunto dan lugar a los vaciados en forma de cuñas de desarrollo métrico que se observan en el talud (Fig 6B, C). En el talud anverso, la rotura más característica es el deslizamiento de estratos capa sobre capa, con un plano de rotura paralelo al del talud, y una potencia del elemento que desliza pequeña en comparación con su longitud, asimilable a un talud infinito (Matos Fernandes, 2020). En el reverso, se desarrollan taludes en extraplomo en los que se registran abundantes desprendimientos de fragmentos rocosos por vuelco.

Una vez reconocidos los materiales y establecida la tipología de inestabilidades, se procede a caracterizar los desprendimientos: áreas fuente, actividad, zonas de acumulación, trayectorias, tamaño y peso de los bloques.

La figura 7A recoge las principales áreas activas en los últimos 3 años, las zonas de acumulación preferencial y se establece la línea de máximo alcance de bloques individuales. En lo que se refiere a los bloques desprendidos, se han realizado un total de 89 medidas de tamaño y peso sobre las caídas identificadas y registradas en las visitas trimestrales realizadas al entorno durante los 3 años de desarrollo de esta investigación. Se discriminan las rocas de menos de 1 kilogramo por razones de operatividad, y se obtiene la distribución recogida en la figura 8, censurada en esta cota inferior.

La distribución obtenida es de carácter potencial, con un gran número de bloques de menor tamaño y peso, que progresivamente desciende a medida que asciende el peso. Los valores máximos alcanzados para las rocas desprendidas en el periodo de investigación no superan los 30 kilogramos. Indicar a este respecto, que en los depósitos se observan bloques caídos de mayor tamaño y peso.

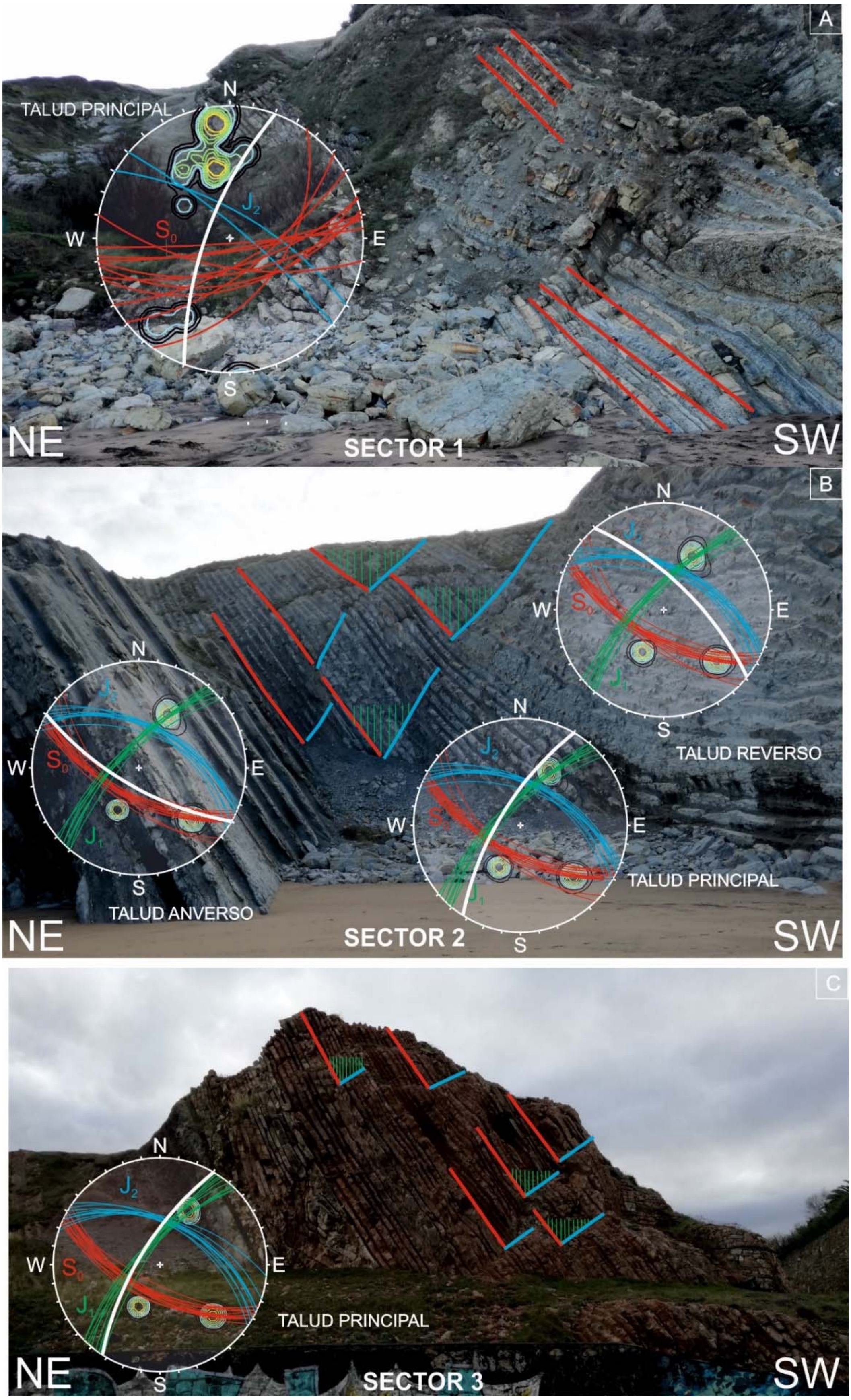


Fig. 6. Tipología de roturas y proyección estereográfica por sectores. A) Sector 1. B) Sector 2. C) Sector 3.

Aunque parte de los mismos pueden tener un origen natural, también podrían estar relacionados con las actuaciones de estabilización realizadas en años previos en la playa y sus acantilados. Esta situación incide directamente en la energía alcanzada por los desprendimientos, por lo que será considerada en posteriores fases de la investigación.

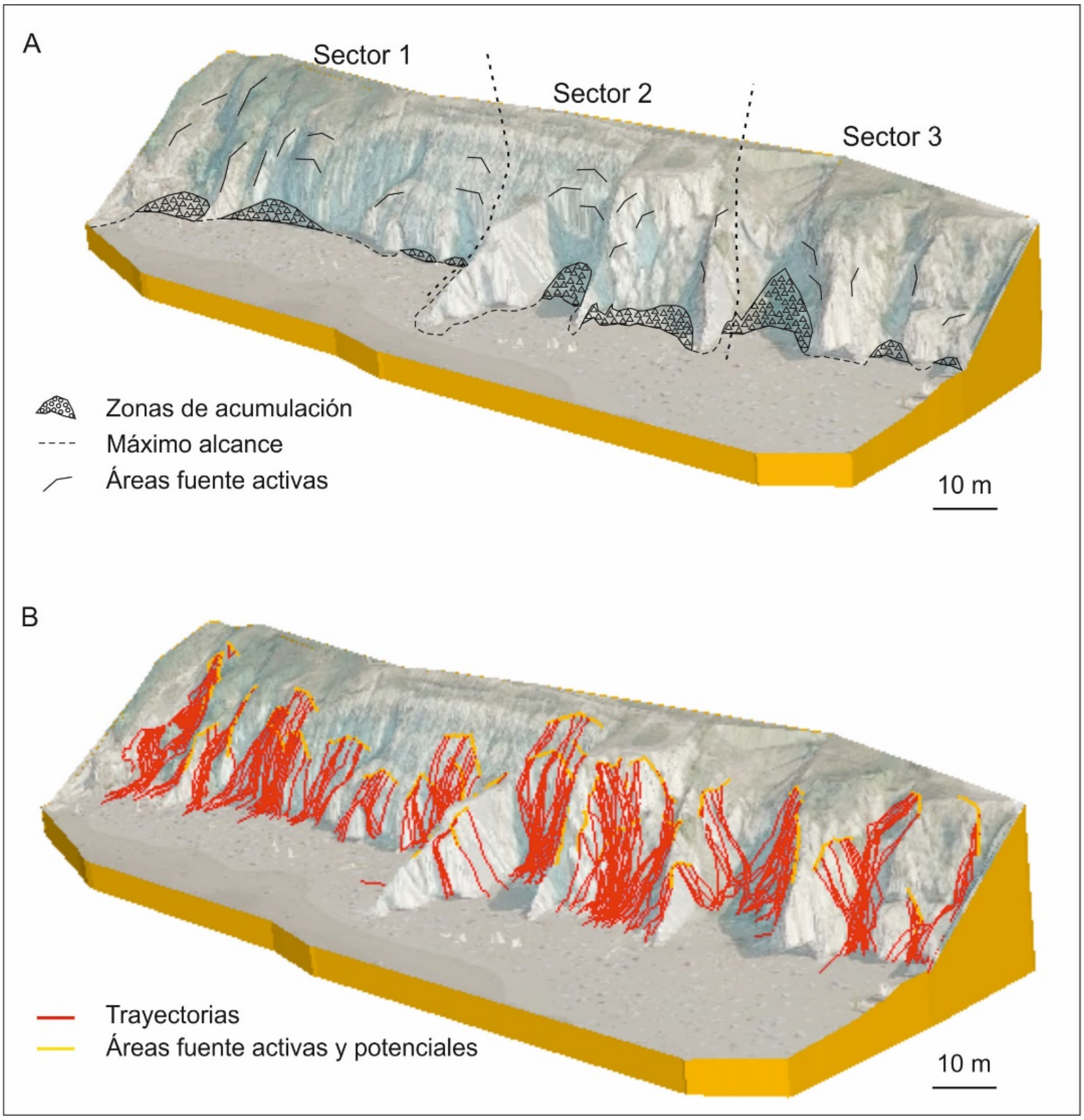


Fig. 7. A) Modelo tridimensional de la playa de Atxabiribil e identificaciones en campo. B) Simulación 3D de caídas de rocas: trayectorias (líneas rojas) y áreas fuente activas y potenciales (líneas amarillas).

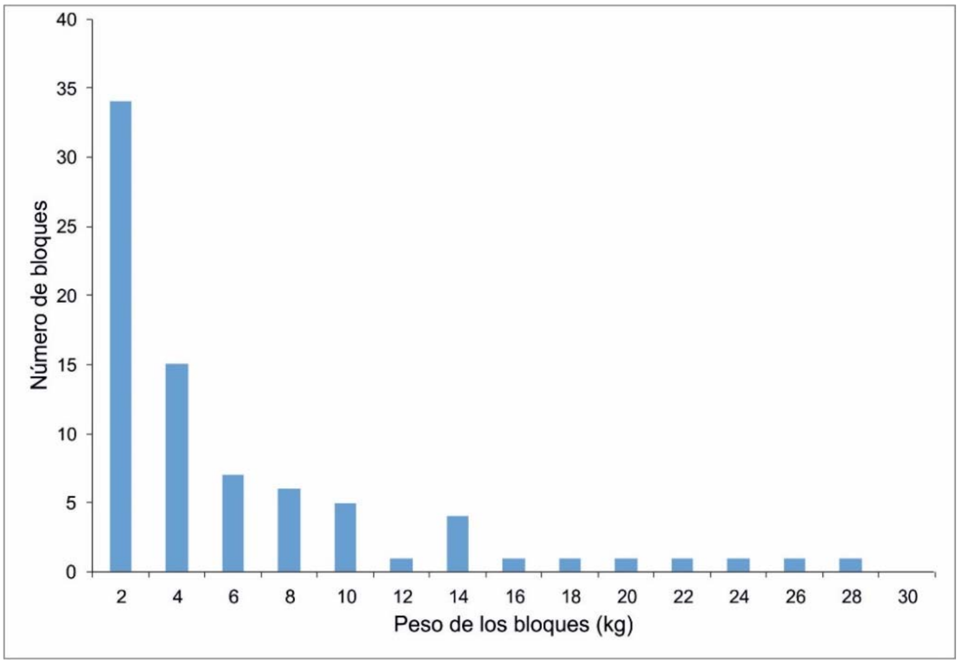


Fig. 8. Histograma de medidas de peso de caídas de roca registradas.

Modelización de caída de rocas en 3D

A partir de la información previa, se ha realizado una modelización de conjunto de la playa de Atxabiribil (Fig. 7B). Para ello se superpone a la malla tridimensional previamente generada la ortofoto georreferenciada y se establecen sobre el modelo los distintos tipos de terreno básicos considerados en esta aproximación: flysch, debris, vegetación y playa.

Seguidamente, se marcan sobre el modelo las áreas fuente activas y potenciales identificadas en campo, y se establece para cada una de ellas el número de trayectorias a modelizar. En el caso de la playa de Atxabiribil, se han definido 23 áreas fuente activas y 12 potenciales, que se sitúan principalmente en los estratos más competentes de los acantilados, y se han realizado un total de 350 simulaciones de caída de rocas, 10 por cada zona. En cuanto al peso de los bloques, se ha considerado un valor de 28 kilogramos, que es el peso máximo registrado en el apartado previo y que ofrece, por tanto, los valores mayores de energía.

La calibración del equipo y de los parámetros resistentes de los terrenos definidos permiten ajustar el modelo para asemejarlo al máximo a la realidad. Siguiendo las orientaciones indicadas en el programa, los parámetros finales utilizados en la modelización correspondientes a restitución normal, tangencial, rozamiento y desviación estándar, se recogen en la tabla 1.

Tabla 1. Valores empleados en la modelización de los desprendimientos: Rn: coeficiente de restitución normal, Rt: coeficiente de restitución tangencial, ϕ: ángulo de rozamiento y Std: desviación estándar.

		Rn	Rt	ϕ	Std
Terrenos	Flysch	0.6	0.9	39	0.4
	Debris	0.5	0.8	39	0.3
	Vegetación	0.3	0.5	30	0.3
	Playa	0.3	0.3	30	0.3

Como resultado, cada línea roja en la figura 7B es una caída de rocas individual, de la que podemos reconocer su trayectoria, tanto frontal como lateral, su alcance desde el pie del talud y energía tanto en su recorrido como de impacto. Las acumulaciones se encuentran mayoritariamente en la base del acantilado y en los entrantes generados por la erosión diferencial, y los máximos alcances de las rocas son de 5 metros desde el pie de talud, aunque principalmente alcanzan máximos de entre 2 y 3 metros (Fig. 7B).

Propuesta de actuaciones

Además de la simulación de trayectorias, la modelización tridimensional permite realizar mapas de distintos parámetros que pueden favorecer la gestión de estos espacios. Para la elaboración de estos mapas, el terreno se divide en celdas de distinto tamaño. En nuestro caso, dado que los acantilados bordean la playa de Atxabiribil y se trata de un área protegida, como se ha indicado previamente, las medidas estructurales no son recomendables. En este punto, resulta fundamental establecer el alcance de los bloques desprendidos y delimitar las zonas activas de caída de rocas, lo que podrá permitir la elaboración de mapas de peligrosidad, con los que orientar la utilización de estos espacios. Con este objetivo, se elaboran los siguientes mapas con celdas de 2x2 metros: número de trayectorias que pasan por cada una de las celdas en que se ha discretizado el terreno (Fig. 9A), energía máxima alcanzada en cada celda (Fig. 9B) y número de impactos de bloques por celda (Fig. 9C). La figura de trayectorias, permite reconocer los recorridos preferenciales de caída de rocas, mientras las de energía máxima y número de impactos informan de la entidad del proceso en distintas áreas del acantilado.

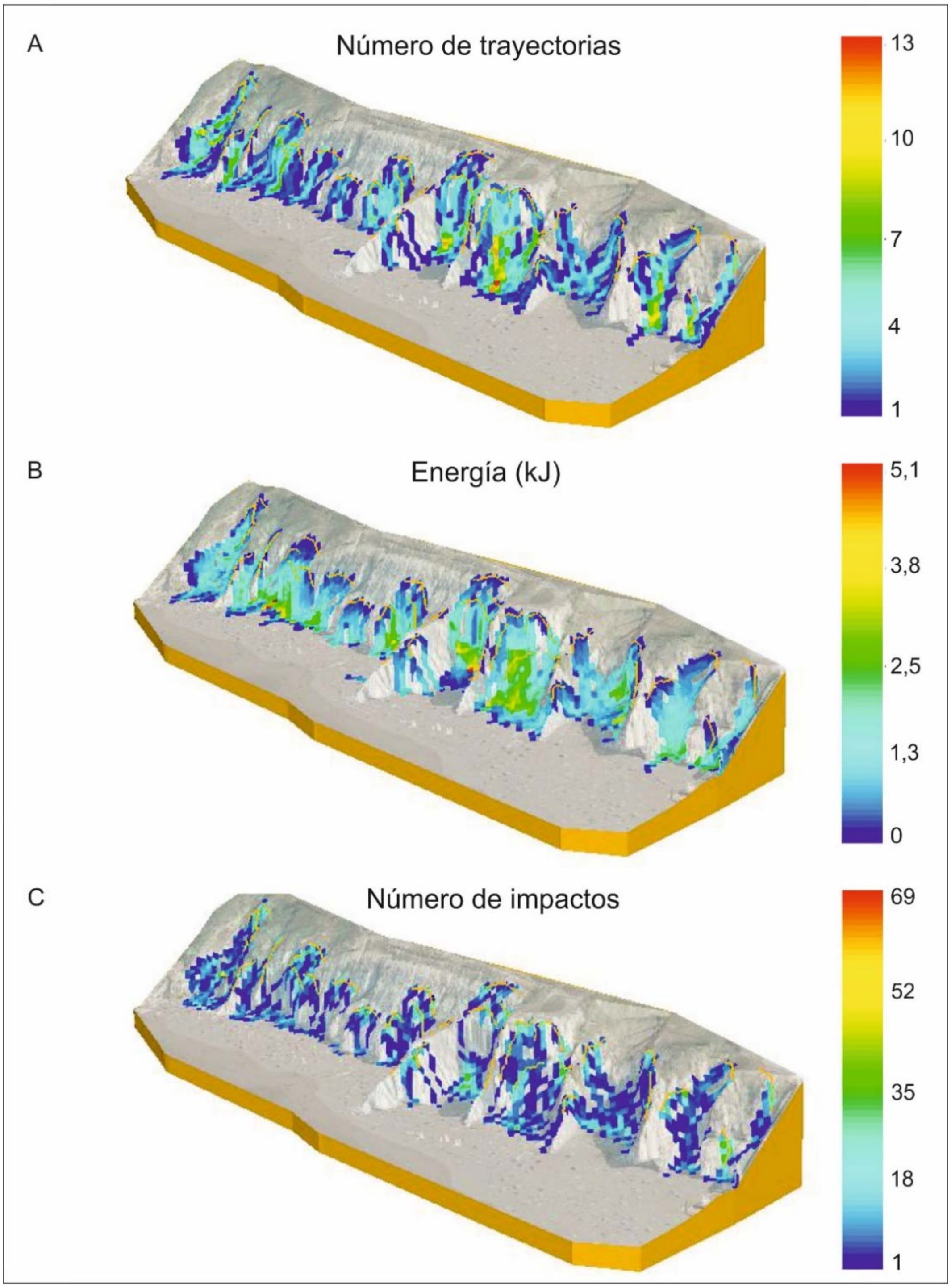


Fig. 9. Mapeos por celdas de algunos parámetros de los procesos de caídas de rocas en la playa de Atxabiribil. A) Número de trayectorias. B) Energía. C) Número de impactos.

A partir de esta información, la relación entre la energía y la recurrencia del proceso, obtenida mediante el seguimiento plurianual de los desprendimientos, determina la peligrosidad por caída de rocas (Fig. 10A). En el caso de la playa de Atxabiribil, la energía individual de las caídas alcanza máximos de 5 kJ, y la recurrencia observada es de entre 20 y 30 caídas al año en los distintos tramos de la playa, lo que según la clasificación establecida por Volkwein et al., 2011, supone un peligro medio. De este modo se realiza un mapa de peligrosidad de la playa en el que se delimitan (Fig. 10B) las zonas activas (desde el talud hasta el alcance máximo) y una zona de seguridad para los usuarios de la playa con un margen de 2 metros, que es el tamaño de celda utilizado. En todo caso, dado que la modelización se ha hecho con observaciones de 3 años de seguimiento, estos márgenes deberán ser contrastados y podrían ser aumentados en la medida en que se disponga de una información más completa del proceso.

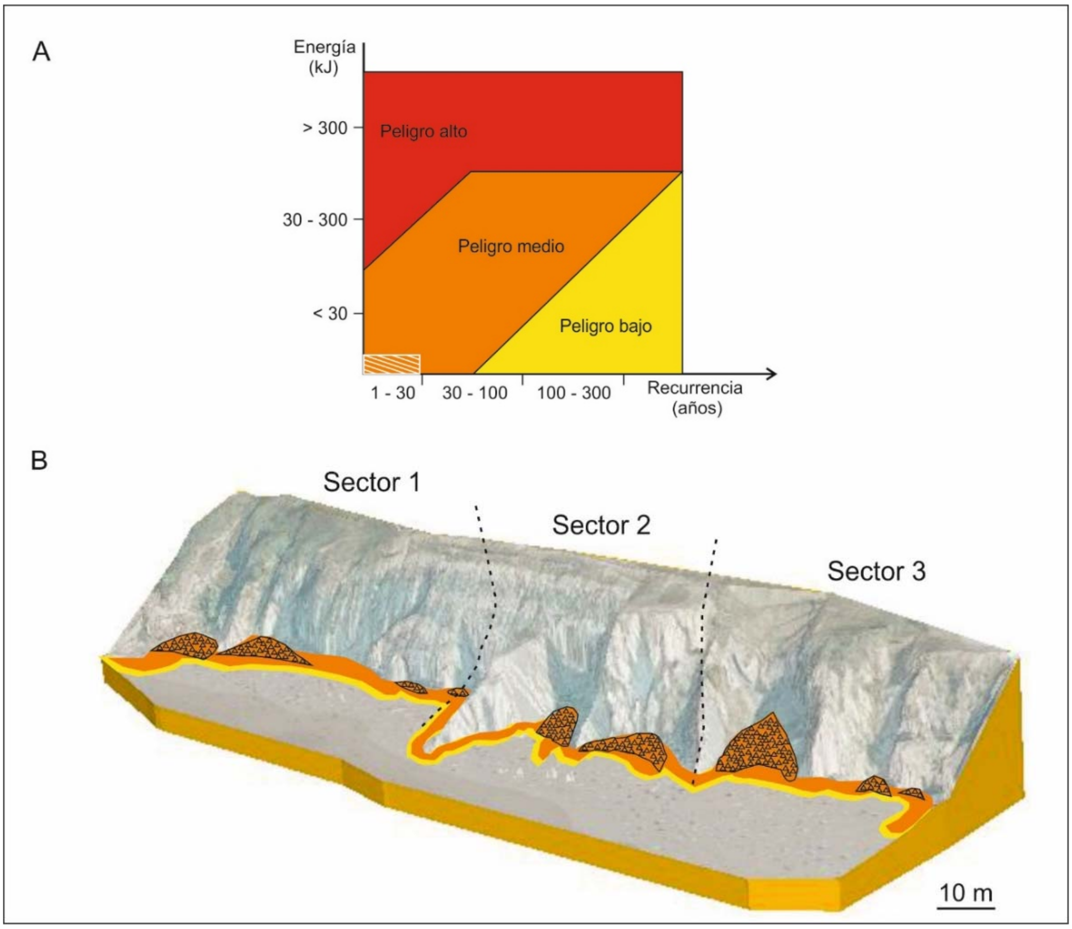


Fig. 10. Mapa de peligrsidad de la playa de Atxabiribil

Discusión y conclusiones

En la playa de Atxabiribil, la aproximación aplicada al análisis de caída de rocas en acantilados costeros permite resaltar el valor de los estudios de detalle para el desarrollo de propuestas de actuación ajustadas a cada espacio. Para ello, las nuevas herramientas de adquisición de información topográfica, fundamentalmente drones y láser escáner terrestres, facilitan la obtención de modelos digitales del terreno de detalle, de forma rápida y eficiente. Se optimiza el trabajo de campo y puede desarrollarse de manera más precisa la localización de áreas fuente, trayectoria y zonas de acumulación de bloques desprendidos. En este estudio, la calidad del macizo rocoso se ha establecido mediante el índice Rock Mass Rating (RMR) de Bieniawski, si bien en futuros trabajos se considera incluir índices específicos para entornos flyschoides, como el GSI (Geological Strength Index) de Marinos y Hoek, 2001. El trabajo de campo se completa con la identificación de los tipos de rotura en el acantilado, y la determinación del peso, dimensiones y alcance de bloques caídos. A partir de esta información, la modelización tridimensional, en nuestro caso utilizando el programa RocPro3D (RocPro3D, 2014), permite precisar la evolución, trayectoria y energía de los desprendimientos.

En este sentido, a partir de los registros de 3 años de seguimiento se establece que la distribución general de frecuencias de peso de bloques caídos sigue una ley potencial, similar a la obtenida de inventarios de caída de rocas recogidos en trabajos previos (Bunce et al., 1997; Hungr et al., 1999; Dussauge-Peisser et al., 2003; Volkwein et al., 2011; Morales et al., 2021), con un valor de bloque máximo de 30 kilogramos. Este valor es utilizado como base para el desarrollo de mapas de peligrosidad, considerando el máximo alcance de los bloques desprendidos y su recurrencia.

Estos resultados posibilitan el desarrollo de estrategias de gestión específicas adaptadas al entorno investigado. En el caso de la playa de Atxabiribil, al tratarse de un espacio protegido donde el acantilado se sitúa directamente sobre la playa, se propone la delimitación de zonas de advertencia. Este tipo de aproximación, basada en el principio de actuación mínima, requiere un proceso de seguimiento, tanto para profundizar en las dinámicas de detalle del entorno, como para verificar las actuaciones planteadas a corto, medio y largo plazo (Morales et al., 2018). En este sentido, en lo que se refiere al análisis de detalle de las dinámicas de caída de rocas, se trabaja en el reconocimiento de posibles relaciones entre las características geomecánicas del macizo rocoso y el desarrollo y evolución de los desprendimientos. Del mismo modo, a medida que se continúe la investigación, se irá recogiendo más información sobre las dimensiones y alcance de los bloques caídos, lo que permitirá validar, o en su caso modificar, los resultados obtenidos. En todo caso, la información recogida permite tener una imagen tridimensional de la situación actual del entorno.

Agradecimientos y financiación

Los autores quieren agradecer a los dos revisores, Dra. Mercedes Ferrer y Dr. Javier Elorza, las correcciones y sugerencias realizadas del manuscrito, que han ayudado notablemente a la mejora del presente trabajo. Del mismo modo, agradecer a la editora de la revista Dra. Nieves López-González por su dirección a lo largo de todo el proceso. El presente estudio ha sido financiado por el grupo de investigación de la Universidad del País Vasco (UPV/EHU) IT-1029/16 (Gobierno Vasco) en el marco del proyecto estratégico “Análisis de inestabilidades en entornos costeros del País Vasco” PES-18/97 (Universidad del País Vasco).

Contribución de autores

Elaboración del trabajo, J.A.C. y T.M.; metodología, J.A.C., T.M. y J.A.U.; obtención de datos, J.A.C., T.M., A.A. y J.A.U.; figuras, J.A.C. y J.A.U.; investigación/análisis, J.A.C., T.M., A.A. y J.A.U.; revisión del manuscrito, T.M. y J.A.U.

Referencias

Alejano, L.R., Gómez-Márquez, I., Martínez-Alegría, R., 2010. Analysis of a complex toppling-circular slope failure. Engineering Geology 114: 93-104.

Álvarez-Llano, I., Baguer, A., Martínez López de Sabando, M., Mugica, J., Pérez-García, J.R., Unanue, L., Elorza, J., 2006. Variaciones de espesor y de contenido en CaCO3 en los pares marga-caliza del Maastrichtiense inferior en Sopelana (Arco Vasco). Geogaceta, 39: 131-134.

Apellániz, E., Lamolda, M.A., Orue-Etxebarria, X., 1983. Posición estratigráfica de las "Calizas del Danés", País Vasco. Revista Especial de Micropaleontología, 15(3): 447-455.

Batenburg, S.J., Gale, A.S., Sprovieri, M., Hilgen, F.J., Thibault, N., Boussaha, M., Orue-Etxebarria, X., 2014. An astronomical time scale for the Maastrichtian based on the Zumaia and Sopelana sections (Basque Country, northern Spain). Journal of the Geological Society, London, 171: 165-180.

Bieniawski, Z.T., 1989. Engineering Rock Mass Classifications: A Complete Manual for Engineers and Geologists in Mining, Civil and Petroleum Engineering, John Wiley & Sons, Inc. United States, 272 p.

Bunce, C.M., Cruden, D.M., Morgenstern, N.R., 1997. Assessment of the hazard from rock fall on a highway. Canadian Geotechnical Journal, 34: 344-356.

Deere, D.U., Hendron, A.J., Patto, F.D., Cording, E.J., 1967. Design of surface and near surface construction in rock. Proceedings of the 8th U.S. Symposium on Rock Mechanics-Failure and Breakage of Rock. American Institute of Mining, Metallurgical and Petroleum Engineers, Inc., New York, 237-302.

Dinarès-Turell, J., Pujalte, V., Stoykova, K., Elorza, J., 2013. Detailed correlation and astronomical forcing within the Upper Maastrichtian succession in the Basque Basin. Boletín Geológico y Minero, 124: 253-282.

Dong, Z., Liang, F., Yang, B., Xu, Y., Zang, Y., Li, J., Wang, Y., Dai, W., Fan, H., Hyyppa, J., Stilla, U., 2020. Registration of large-scale terrestrial laser scanner point clouds: A review and benchmark. ISPRS Journal of Photogrammetry and Remote Sensing, 163: 327-342.

Dussauge-Peisser, C., Grasso, C., Helmstetter, A., 2003. A statistical analysis of rockfall volume distributions: Implications for rockfall dynamics. Journal of Geophysical Research: Solid Earth, 108: 1-11.

Emery, K.O., Kuhn, G.G., 1982. Sea cliffs, their processes, profiles, and classification. Geological Society of America Bulletin, 93: 644-654.

Fan, L., Smethurst, J.A., Atkinson, P.M., Powrie, W., 2015. Error in target-based georeferencing and registration in terrestrial laser scanning. Computers & Geosciences, 83: 54-64.

Feuillé, P., Rat, P., 1971. Structures et paléogéographies pyrénéo-cantabriques. En : Histoire structural du Golfe de Gascogne, Tome 2, (Debyser, J., Le Pichon, X., Montardet, L., Eds.). Publication de l'Institute Fraçais du Pétrole, Collection et Séminaires, Technip, Paris, 1-48.

Hungr, O., Evans, S., Hazzard, J., 1999. Magnitude and frequency of rockfalls and rock slides along the main transportation corridors of south-western British Columbia. Canadian Geotechnical Journal, 36: 224-238.

Iridoy, P., Zudaire, S., Azaguirre, M., Dorronsoro, A., Olano, G., Beriain, E., Usarbarrena, A., Elorza, J., 2010. Variaciones de color y contenido de CaCO3 en los pares marga-caliza del Maastrichtiense superior y Eoceno inferior en Sopelana (Arco Vasco): reflejo de cambios paleoambientales. Geogaceta, 49: 91-94.

Lamolda, M.A., Orue-Etxebarria, X., Proto-decima, F., 1983. The Cretaceous-Tertiary boundary in Sopelana Biscay, Basque Country). Zitteliana, 10: 663-670.

Li, X., Dong, M., Jiang, D., Li, S., Shang, Y., 2020. The effect of surface roughness on normal restitution coefficient, adhesion force and friction coefficient of the particle-wall collision. Powder Technology, 362: 17-25.

Margottini, C., Spizzichino, D., 2014. The management of cultural heritage in sites prone to natural hazard. Memorie Descrittive della Carta Geologica d'Italia. XCVI: 415-430.

Margottini, C., Gigli, G., Ruther, H., Spizzichino, D., 2016. Advances in sustainable conservation practices in rupestrian settlements inscribed in the UNESCO's World Heritage List. Procedia Earth Planet Science, 16: 52-60.

Marinos, P., Hoek, E., 2001. Estimating the geotechnical properties of heterogeneous rock masses such as flysch. Bulletin of Engineering Geology and the Environment, 60: 85-92.

Matos Fernandes, M., 2020. Analysis and Design of Geotechnical Structures. CRC Press. 754 pp.

Morales, T., Uriarte, J.A., Damas, L., Antigüedad, I., 2018. Taludes inestables y patrimonio cultural: cómo y hasta dónde actuar. Una visión desde las Galerías Punta Begoña (Getxo, Bizkaia). VI. Congreso GEIIC, Vitoria-Gasteiz.

Morales, T., Clemente, J.A., Damas Mollá, L., Izagirre, E., Uriarte, J.A., 2021. Analysis of instabilities in the Basque Coast Geopark coastal cliffs for its environmentally friendly management (Basque-Cantabrian basin, northern Spain). Engineering Geology, 283: 106023.

Pandzic, J., Pejic, M., Bozic, B., Eric, V., 2017. Error model of direct georeferencing procedure of terrestrial laser scanning. Automation in Construction, 78: 13-23.

Pfeiffer, T.J., Bowen, T.D., 1989. Computer simulation of rockfalls. Bulletin of the International Association of Engineering Geolology 26, 135–146.

Pujalte, V., Baceta, J.I., Orue-Etxebarria, X., Payros, A., 1998. Paleocene strata of the Basque Country, western Pyrenees, northern Spain: Facies and sequence development in a deep-water starved basin. En: Mesozoic and Cenozoic Sequence Stratigraphy of European Basins: SEPM (Graciansky, P.C., Hardenbol, J., Jacquin, T., Vail, P.R., Eds.). Society for Sedimentary Geology, 60: 311-325.

QGIS 3.8: Zanzíbar, 2019. https://qgis.org/es/site/forusers/download.html

Ramírez del Pozo, J., 1973. Síntesis geológica de la provincia de Álava. Obra cultural de la Caja de ahorros de la Ciudad de Vitoria, Vitoria-Gasteiz.

RocPro3D, 2014. RocPro3D software. http://www.rocpro3d.com/rocpro3d_en.php

RocScience, 2013. Dips, analyze orientation-based geological data. Rocscience's User's Guide. https://www.rocscience.com/software/dips

Rodríguez, L., Esteban, J.J., Vegas, N., Cuevas, J., 2008. Tectónica de inversión en la Playa de Sopelana (Arco Vasco, Pirineos occidentales). Geogaceta, 45: 23-26.

Spizzichino, D., Condori Amaru, J., Gallego Revilla, J.I., Lombardi, L., Fernandez Merodo, J.A., Margottini, C., 2019. Hydro Geological hazard and mitigation measures for the conservation of Akapana Pyramid in the Tiwanaku archaeological site (Bolivia). En: Monitoraggio e Manutenzione nelle Aree Archeologiche. Cambiamenti climatici - Dissesto idrogeologico - Degrado chimico ambientale. Roma, 265-268.

Tonmoy, F.N., Wainright, D., Verdon-Kidd, D.C., Rissik, D., 2018. An investigation of coastal climate change risk assessment practice in Australia. Environmental Science and Policy, 80: 9-20.

Volkwein, A., Schellenberg, K., Labiouse, V., Agliardi, F., Berger, F., Bourrier, F., Dorren, L.K.A., Jaboyedoff, M., 2011. Rockfall Characterisation and structural protection- A review. Natural Hazards and Earth System Sciences, 11: 2617-2651.

Young, A.P., Carilli, J.E., 2019. Global distribution of coastal cliffs. Earth Surface Processes and Landforms, 44: 1309-1316.

https://www.geo.euskadi.eus/s69-15375/es/ (Última visita: septiembre de 2021).

4.3. Capítulo III: Assessment of long-term structural movements in a historic Cliffside construction through Lomb-Scargle spectral analysis of unevenly spaced time records: The Punta Begoña Galleries (Getxo, Spain)

Vista panorámica de las Galerías Punta Begoña en Getxo

Bulletin of Engineering Geology and the Environment

Volume 81: 485 (2022)

J.A. Uriarte, R. Morales-Juberías, **J. A. Clemente**, I. Antigüedad, T. Morales

https://doi.org/10.1007/s10064-022-02990-8

Abstract

Long-term monitoring of structural movements in historic buildings and heritage sites allows assessing their stability and recognizing damages that require intervention. The Punta Begoña Galleries, built in the earlier part of the 20th century, present pioneering techniques in the use of reinforced concrete in building construction. They stand directly over a coastal cliff, and their recovery requires first to guarantee their stability, while maintaining their historic and patrimonial values. Thus, with the goal of analyzing their global stability, as well as the extent of the observed damages, we implemented a motion monitoring network that includes three boreholes for extensometric control, an inclinometer, and five crack gauges (crackmeters). This monitoring was complemented with the recording of hydrometeorological variables at the surface and in four piezometers. The spectral analysis of the signals of movements was performed by introducing the use of the Lomb-Scargle (LS) periodogram, which is particularly well-suited for the analysis of unevenly spaced time series. This analysis allowed us to differentiate the reversible seasonal elastic components of the records and to recognize the irreversible long-term plastic displacements, which highlight the sectors with active instability. In our case, the identified damages are related to two local problems of building support. Even though the irreversible component of the displacement after seasonal sinusoidal detrending is small (with maximums up to 0.12 mm/y), it does imply a dynamic plastic deformation, which calls for the need to adopt structural stabilization measures.

Keywords: Heritage sites stability · Long-term monitoring · Lomb-Scargle periodogram · Damage assessment · Conservation plan

Introduction

Conservation and stabilization projects in environments of well-known cultural relevance, not only must address the repairs of any existing damages, but also must ensure the preservation of the historical value of the site (Guo et al. 2009). Thus, and following the recommendations compiled in the "ICOMOS Charter – Principles for the analysis, conservation and structural restoration of architectural heritage (2003)", the rehabilitation measurements aim to address the root of the problems while being minimally invasive in order to guarantee the safety and durability of the site and to mitigate damage to the patrimony.

Consequently, the diagnosis and knowledge of both the building techniques and the processes of alteration and structural damages are fundamental to rehabilitate and repurpose the historic building (Heinemann 2008, 2013; ICOMOS 2010, 2014; Laborde Marqueze 2013; Custance-Baker and Mac Donald 2014). The diagnosis must follow specific methodologies in order to understand the structure and building methods, to characterize the alteration processes, and to evaluate and control the structural safety of the site (Chang el al. 2003; ICOMOS 2003; Heinemann 2008; Laborde Marqueze 2013; Damas Mollá et al. 2018, 2020). For cultural heritage and archaeological sites considered to be affected by geologically based issues and geo-hazards, monitoring strategies incorporate a wide range of complementary survey techniques (Margottini et al. 2015; Themistocleous and Danezis, 2019); including, at the local-scale (Themistocleous et al. 2018), in-situ observation, 3D laser scanning, differential GNSS, satellite and ground-based radar interferometry, UAV imagery (Colomina and Molina 2014; Tang et al. 2016), along with geotechnical instrumentation for displacement control, mainly extensometers and crack gauges (Ding et al. 2000; Greif et al. 2006; Mulas et al. 2020), and environmental sensors.

It is within this framework that we approach the recovery and revalorization of the Punta Begoña Galleries (Getxo, Spain). Previous reports question the overall stability of this early 20th century building. The stability of its most significant spaces, namely the Northwest and Southwest Galleries, in relation to the stability of the cliff upon which they were built was highly questioned, leading to pose the need to demolish the building and only preserve architectural elements of the façade. In this context, given the local development of the damage observed, and the fact that these are extremely slow movements, in the sense that they do not pose an immediate threat to the structure, but have proven to be detrimental over the long course of time (Greif et al. 2006), a permanent geotechnical recording system (Cempel 2003; De Stefano et al. 2016) was designed in order to monitor the instability symptoms. This geotechnical monitoring system is chiefly based on wire-extensometers and crack gauges seeking to identify the behavior of this dual context in which the development of instabilities in the cliff can lead to the development of damage to the building's structure, whose supports in turn alter the state of the terrain's original stresses.

Records from these devices are affected by temperature changes giving rise, due to materials thermal dilatancy, to opening-closing cycles in the time-series that can mask significant and worrisome small irreversible displacements (Weber et al. 2017; Janeras et al. 2017; Mulas et al. 2020). To separate these reversible (elastic) components from the signals and quantify the irreversible (plastic) displacements, Weber et al. (2017) have proposed a linear fit method between temperature and fracture opening. This approach requires temperature series, so Mulas et al. (2020) propose a sinusoidal wave fit of displacement time series, avoiding the consideration of temperature series that may lead to biased results as they observed significant time-lag of the temperature signal with depth. In this work, we introduce the use of the Lomb-Scargle spectral analysis of the time-series (Lomb 1976; Scargle 1982). The Lomb-Scargle analysis can be understood as a Least-Squares Spectral Analysis (LSSA) method. This technique was originally developed for the analysis of astronomical time-series, but it has been adopted to analyze time-series in different geology fields such as environmentology, climatology and paleoclimatology (Pestiaux and Berger 1984; Schulz and Stattegger 1997; Hocke and Kampfer 2009), seismology (Park et al. 1987) and cyclostratigraphy (Weedon 2003; Pardo-Igúzkiza and Rodríguez-Tovar 2011; Vaughan et al. 2015). The main advantage of this method is the ability to overcome the limitations imposed by other methods that require continuous and evenly spaced time-series; thus, this method eliminates the need to fill unevenly sampled time-series with interpolated values, which can have an effect on the spectral analysis results (Schulz and Stattegger 1997; Pardo-Igúzkiza and Rodríguez-Tovar 2012).

Our main objective is to analyze the efficiency of the installed monitoring network, as the basis of a cliff and structural health monitoring system, and to show how the Lomb-Scargle spectral analysis can be used to quantify the magnitude of the instabilities and the scope of the damages. This information will be essential for the design of mitigation strategies that would preserve the natural and cultural value of the cliff-structure complex, while incorporating the necessary safety measures for its public use.

Construction context

The Punta Begoña Galleries are located in the municipality of Getxo, on the coastal cliffs of this sector of the Bay of Biscay (Fig. 1). Designed by Ricardo Bastida as an extension of Horacio Etxevarrieta's house, the galleries were built directly on the rocky wall of the cliff, constituting a watchtower over the entrance of Bilbao’s Estuary.

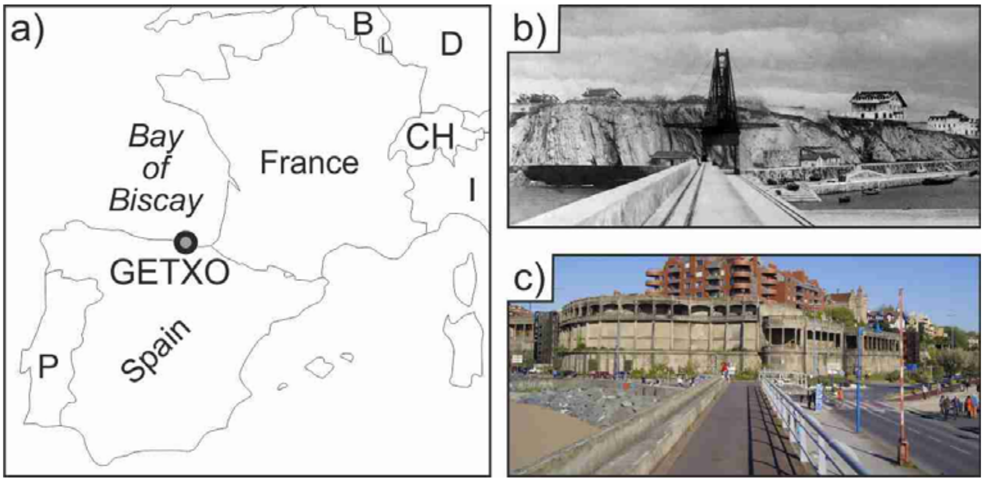


Fig. 1 (a) Geographical location (b) image prior to construction (c) Punta Begoña Galleries today.

From a geological point of view, materials outcropping in this sector of the coast are Mesozoic and Cenozoic successions of marine deposits folded during the Alpine Orogeny (Morales et al. 2004). In the area where the galleries were built, these materials show a flyschoid alternation, consisting of hemipelagic marls and marly limestones (Upper Cretaceous gray and red marls and marly limestones). The arrangement of rock strata shows a northwest-southeast direction dipping deeply towards the south.

In this geological context, Punta Begoña Galleries were built at the beginning of the 20th century, adapting its shape and structure to the morphology of the cliff (Figs. 1b, c). Their origin appears to be related to a rockfall that made necessary the stabilization of the area. The architect Ricardo Bastida designed, for this purpose, a wall with out-facing pavilions in 1918, which eventually resulted, in 1921, in a more ambitious construction: the current galleries. The final building structure resulted in two main façades that are perpendicular to each other: the so-called Northwest Gallery, with a large room, called the Hall, followed by an elevated corridor; and the Southwest Gallery (Fig. 2a). The galleries are separated by a semicircular structure, known as the "Tholos" that acts as a juncture.

Their construction coincided with the beginning of the use of reinforced concrete (Rosell and Cárcamo 1994; Díaz Morlán 1999, 2011). The façades are based on a sandstone masonry wall (Figs. 2b, d), on which an intermediate section of reinforced concrete blind wall was built. The blind wall supports a corridor gallery with concrete columns and prefabricated balustrades, crowned by an upper garden. The pillars of the structure are also made of reinforced concrete and were built directly on the original cliff (Figs. 2c, e, f), resting on small footings excavated in a staggered manner. An important aspect to highlight is the differing relationship between the rocky cliff and the structure of the building on both façades. Namely, while the orientation of the Northwest Gallery façade is perpendicular to the direction of the strata (Fig. 2c), the direction of the stratification and the façade of the Southwest Gallery are parallel (Figs. 2e, f).

Consequently, after years of neglect, when in 2014 the Getxo City Council promoted the recovery and enhancement of this heritage site, it emerged as a priority issue to establish the nature and extent of the damages to the building. Initially, its general stability in relation to the cliff-construction interaction was particularly questioned, so a monitoring strategy was designed with the aim of measuring and assessing the observed damage.

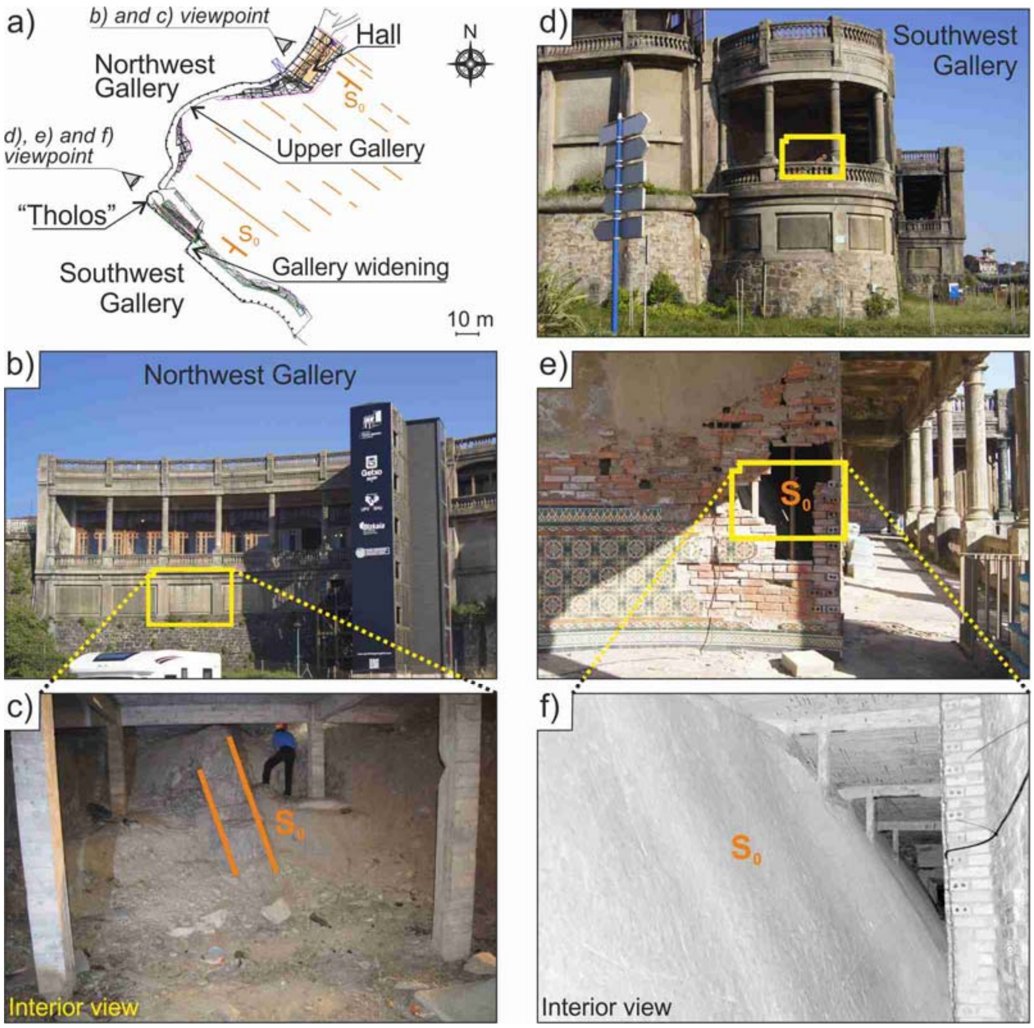


Fig. 2 (a) Plan of the Punta Begoña Galleries (b) exterior of the Northwest Gallery Hall (c) interior space underneath The Hall, showing the pillars standing on the cliffside (d) and (e) exterior of the Southwest Gallery (f) interior showing the supporting pillars over the chalky strata. S0: stratification.

Methodology

Movement control network

As a first step, in order to have a highly accurate digital reference to include the different observations of the building, we created a geometrical model of the building and its supports in the rocky slope. For this, a Terrestrial Laser Scanner (TLS), with a FARO Laser Scanner Focus 3D X330 equipment was used to make a full scanning of the building and the rocky slope. The TLS is an ideal technique for buildings with irregular and not very accessible morphologies (Casula et al. 2009; Montuori et al. 2014; Dong et al. 2020). The 3D Point Cloud (3DPC) clearly depicts both the detailed structure of the building and the cliff. The 3DPC is essential for the detailed management of high value heritage elements, before acting on them. In our project, the software Web Share 2 Go (FARO 3D Visionary) enabled real viewing of the scanned space through an external cloud service, which allowed us to make measurements. We completed planimetrics based on the 3DPC point cloud using CAD software.

Based on this planimetric model, and after reviewing the building's structural damages, we set up the movement monitoring network together with a hydrogeological control system (Fig. 3):

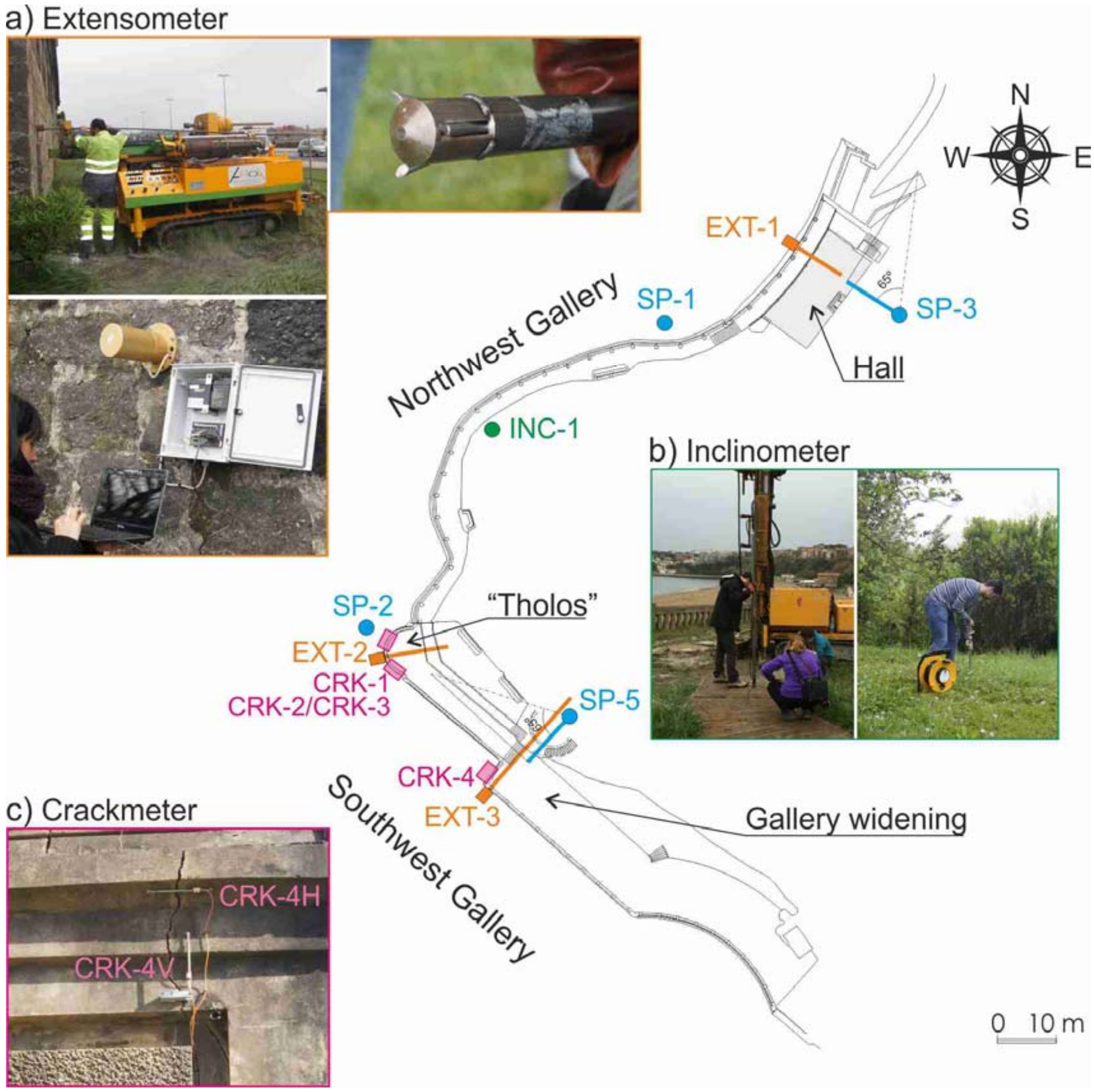


Fig. 3 Movement control and hydrogeological monitoring devices in Punta Begoña Galleries. Equipment installation: (a) extensometers (b) inclinometer (c) crackmeters. EXT: borehole for extensometric control. CRK: crackmeter. INC: inclinometer. SP: piezometer.

Northwest Gallery

The area known as “the Hall” is located here. This is the area where most activity is registered by researchers and where the main social and outreach events take place, including thematic workshops and some of the most attended activities open to the public, such as the regular venue for the International Image Festival Getxofoto (www.getxophoto.com).

In this façade (Fig. 4a), despite the orientation of the strata being perpendicular to the slope, and therefore favorable for stability, previous reports identified a crack, with a maximum aperture of 1 cm, in the upper concrete slab at its northeastern corner (Fig. 4b), coinciding with the access stairway to the building from the upper esplanade. This observation was interpreted as a sign of global instability of the building in relation to the cliff, so the first extensometer set (EXT-1) was installed in 2014 from the lower masonry wall of the galleries (Fig. 4a). For this purpose, an 11 meters deep horizontal drilling was carried out, with a diameter of 101 mm for the first 3.60 m, and of 86 mm for the remaining depth. This drilling went through 1.20 m of wall, clayey fills of anthropic nature up to 3.40 m deep, 0.20 m of fragmented rock without matrix, and marly rocks and marly limestones up to the end of the drilling. We then performed the extensometric control by placing 2 potentiometric sensors arranged in an external head, with two sets of rods fixed with hydraulic anchors (Fig. 3a): from 2.50 to 3.25 m (short rod) and from 10.00 to 10.75 m (long rod), respectively (Fig. 4a). The measuring range of the IKM potentiometers (DPF Sensors) is 50 mm, with an accuracy of ±0.01 mm. A Campbell Scientific CR200X Series datalogger recorded, at the desired time step, environmental temperature and ground movements on both rods. The frequency of data recording has varied throughout the research period, as needed, from hourly to every 4 to 12 hours.

Slightly further south, in the most prominent zone of the original cliff, and therefore of the building, we decided (in 2016) to perform one inclinometric drilling (INC-1) from the upper esplanade. The borehole reaches a depth of 21 m, with a diameter of 101 mm. Initially, it passed through 1.20 m of loose material and fill before reaching the rock massif, consisting of an alternation of marls and marly limestones. This borehole was equipped with an inclinometric pipe. The inclinometric measurements were made with a Soil Instruments C17-pro biaxial probe with a monthly periodicity, which allows quantifying the relative horizontal movements on a vertical line.

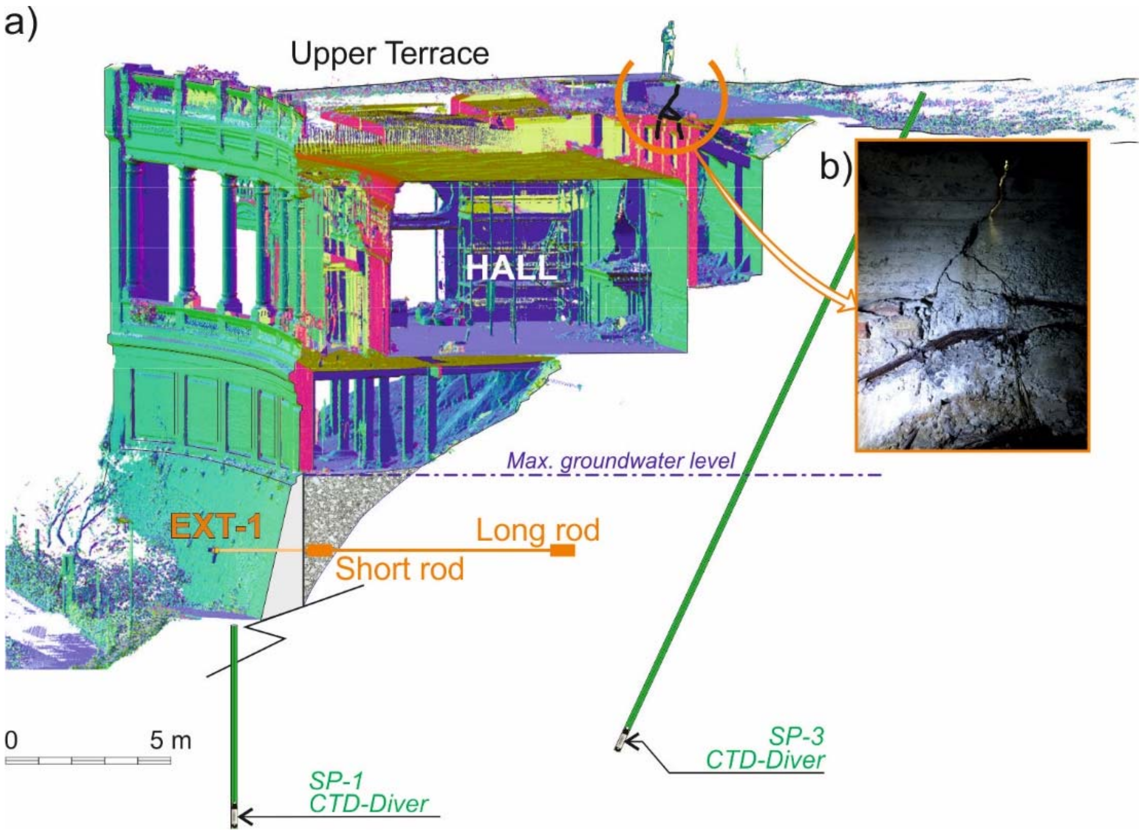


Fig. 4. (a) Schematic cross-section of the Point Cloud of the Punta Begoña Galleries in the Hall, with the location of the EXT-1 extensometer, SP-1 and SP-3 piezometric boreholes (b) image of the existing crack in the upper slab of the building.

At the same time we installed a hydrogeological monitoring system (Fig. 4a), consisting of two piezometers, one located on the upper terrace of the building (SP-3 piezometer) and the other at its base (SP-1 piezometer). Each of these piezometers were equipped with water temperature, water level, and electric conductivity control devices (CTD-Divers) from the brand

Schlumberger. In both boreholes, barometric devices were also installed at 20 cm depth to record air temperature and pressure. Figure 4 shows the monitoring network in the area around the Hall.

Southwest Gallery

Unlike in the Northwest Gallery, the direction of the façade in the southwest side of the building is parallel to the stratification. The stability of this gallery was compromised as part of the structure was loaded on the original cliff strata (Fig. 2f and 5a). In fact, the Southwest Gallery is the sector that shows the main damages, including several cracks affecting its structure, particularly in two well-localized sectors: the "Tholos", with a maximum crack aperture of 1 cm (Fig. 5d), and the section where the gallery widens, in which cracks reach 2 cm of aperture in the upper terrace (Fig. 5b) and up to 1 cm in other parts of the building, as in the façade (Fig. 5c).

With the aim of analyzing the evolution of damages in both sectors, two extensometric control units were implemented in 2014 (EXT-2) and 2016 (EXT-3). The extensometer set EXT-2 was located in the "Tholos" (Figs. 3 and 5). To install it, we carried out a horizontal drilling of 9 m in length and a diameter of 101 mm for the first 1.10 m, and 86 mm for the rest of its length. After 1.30 m of masonry wall, we reached the marls and marly limestones of the rock massif on which the “Tholos” rests. Two potentiometric measurement sensors were installed, with the technical characteristics previously indicated, as well as two sets of rods with hydraulic anchors from 2.5 to 3.25 m (short rod) and 8.00 to 8.75 m (long rod), respectively.

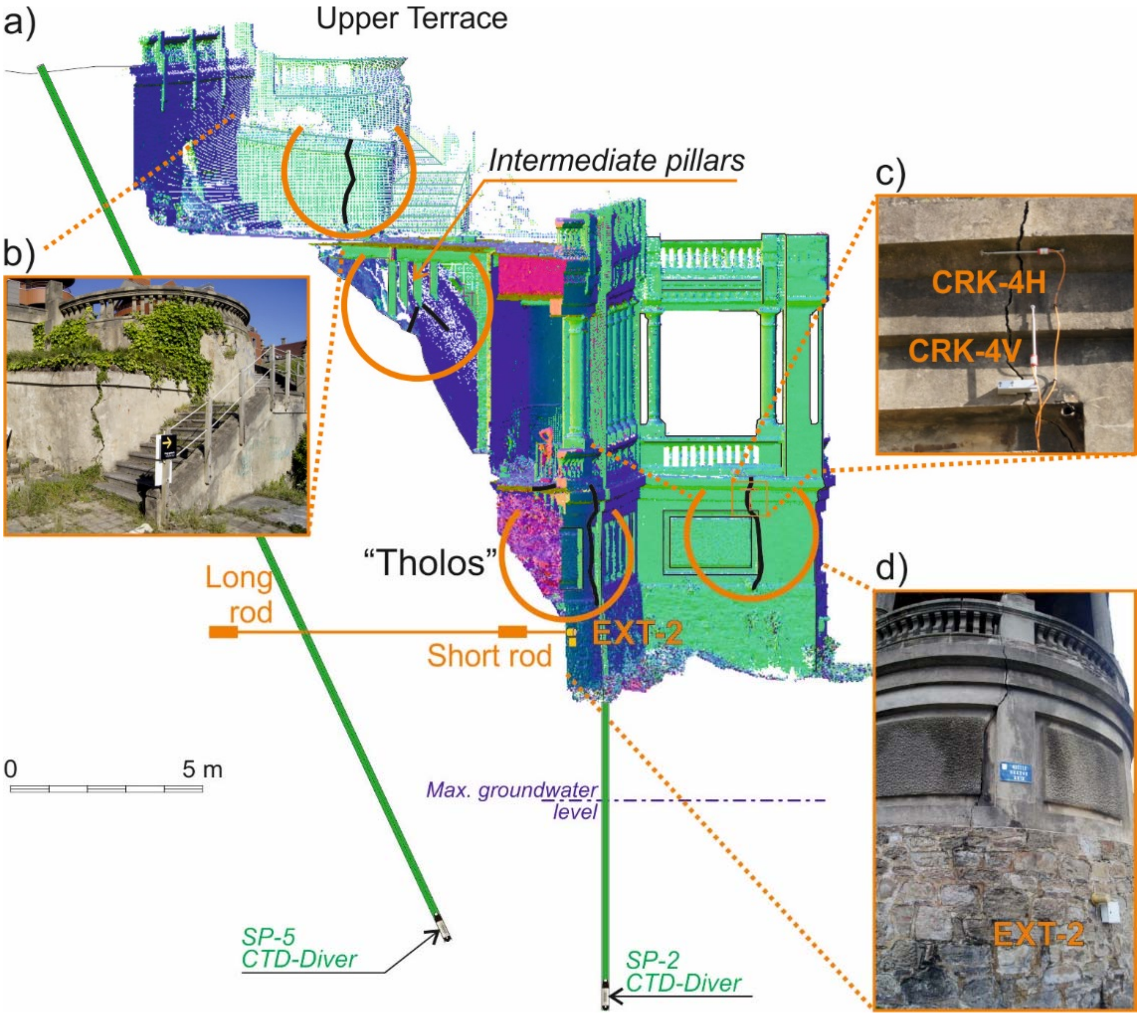


Fig. 5 (a) Schematic cross-section of the Point Cloud of the Punta Begoña Galleries in the "Tholos" and Southwest Gallery (b) and (c) images of the main cracks in the section where the gallery widens (d) main crack in the "Tholos" façade.

The extensometer set EXT-3 was installed in the outer façade corner where the Southwest Gallery widens (Fig. 3). For this purpose, a 20.80 m horizontal drilling was made, with a diameter of 101 mm along its entire length. Due to its parallel disposition to the wall, it ran along the wall for 5.30 m, where it reached the marls and marly limestones of the rocky substrate on which the corner rests. The control equipment has a head with two OG400VW vibrating wire sensors (OTR) and two sets of rods with hydraulic anchors fixed from 10.00 to 10.75 m and from 19.50 to 20.25 m, respectively. The measurement range of these sensors is 50 mm, with an accuracy of ±0.1 mm. The Geosense Geologger LINX data logger continuously records the environmental temperature and the movements of both rods. The periodicity of data acquisition was varied as needed.

In order to monitor the activity of the main cracks in this gallery, five crackmeters were installed: three KLR potentiometric ones (Novotechnik) at the "Tholos" (CRK-1, CRK-2 and CRK-3), with an accuracy of ±0.05 mm; and two VWDT vibrating wire (Geosense VW) on the façade where the Southwest Gallery widens, with an accuracy of ±0.05 mm, named CRK-4H and CRK-4V (set CRK-4). The data were recorded in the same data loggers that collected the extensometric information and with the same periodicity, ranging from 1 h to 12 h increments.

Monitoring in this sector was also completed with two piezometers (Fig. 5), one in the upper terrace (SP-5) and the other at the foot of the galleries (SP-2).

<u>Spectral analysis of data series</u>

From the information obtained in the field campaign, we used the time-series analysis to differentiate between the reversible tendencies characterized by cyclic components, representative of elastic behavior, and the irreversible tendencies that would point to the existence of plastic deformations.

To this end, after importing the data with the *pandas* data analysis tool (McKinney 2010; Reback et al. 2020), first we performed a least-squares linear fit to all the signals to remove any linear trend. After removing the linear trends and the mean from our signals we performed a spectral analysis using the Lomb-Scargle method (Lomb 1976; Scargle 1982) to identify the most dominant periods of cyclic reversible changes. To perform the calculation of the periodogram we used the *gastpy* package developed by VanderPlas and Ivezić (2015). Specifically we use the fast periodogram implementation based on the algorithm developed by Press and Rybicki (1989).

For a data series x_n sampled at nonuniform times t_n the expression for the Lomb-Scargle periodogram is given by:

$$P_{LS}(f) = \frac{1}{2}\left\{\frac{(\sum_n x_n cos(2\pi f[t_n-\tau]))^2}{\sum_n x_n cos^2(2\pi f[t_n-\tau])} + \frac{(\sum_n x_n sin(2\pi f[t_n-\tau]))^2}{\sum_n x_n sin^2(2\pi f[t_n-\tau])}\right\}, \quad (1)$$

where f is the frequency and τ is an offset specified for each frequency to ensure time-shift invariance:

$$\tau = \frac{1}{4\pi f} tan^{-1}\left(\frac{\sum_n sin(4\pi f t_n)}{\sum_n cos(4\pi f t_n)}\right) \quad (2)$$

When written in this form, the expression for the periodogram resembles that of the classical periodogram of evenly sampled data using the Fourier transform. The Lomb-Scargle method can also be interpreted in terms of a least-squares fit to a sinusoidal function at each frequency of the form:

$$y(t,f) = A_f sin\left(2\pi f\left(t - \varphi_f\right)\right) \quad (3)$$

where the amplitude A_f and the phase φ_f parameters can vary as a function of frequency and are fitted to the data using a least-squares method (VanderPlas 2018). In our case, we use:

$$y(t,f) = A_0 + A_f sin\left(2\pi f\left(t - \varphi_f\right)\right) \quad (4)$$

where A_0 is the average value of the oscillation, which depends on the initial setting of the equipment.

Results

<u>Monitoring data</u>

In this section, we present the results obtained from the crackmeter set CRK-4, and extensometers EXT-1 and EXT-2, which are the three control units that provided the most significant information regarding the cliff-building stability. In order to allow for a comparative view of the data registered by these instruments, in Fig. 6 we include the direct observations obtained from 2015 to 2019.

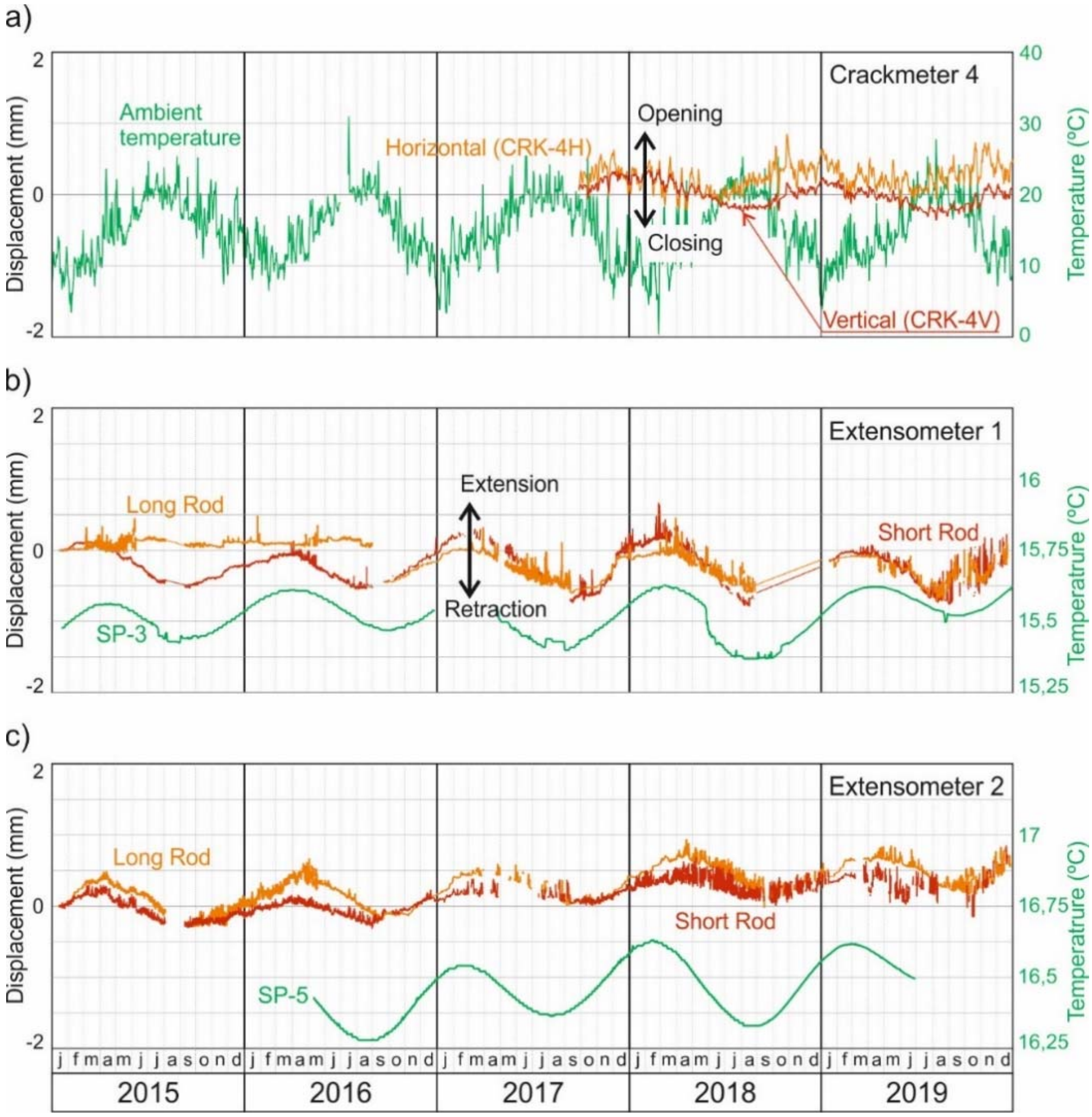


Fig. 6. Records from 2015 to 2019: (a) crackmeter CKR-4, horizontal (CRK-4H) and vertical (CRK-4V) movements, together with the ambient temperature at Punta Galea weather station (b) extensometer EXT-1 long rod (anchored at 10.00 to 10.75 m depth) and short rod (anchored from 2.50 to 3.25 m depth), together with temperature evolution at SP-3 (c) extensometer EXT-2 long rod (anchored at 8.00 to 8.75 m depth) and short rod (anchored from 2.5 to 3.25 m depth), together with temperature at SP-5 piezometer.

Thus, in Fig. 6a, we show the data from the crackmeter set CRK-4, which registers the horizontal (CRK-4H) and vertical (CRK-4V) displacements in the façade's main crack in the sector where the Southwest Gallery widens (Fig. 5c). Both signals show a clear periodicity, with a peak to peak amplitude of 0.566 mm for the horizontal displacement (CRK-4H) and of 0.403 mm for the vertical displacement (CRK-4V). In this figure, we also show the variation in ambient temperature recorded in the nearby weather station of Punta Galea (Getxo). The daily average temperatures also show a clear seasonal tendency, with highs of up to 25 ºC during the summertime and lows of 5 ºC during the wintertime. As can be seen, the displacements in the crack show a logical inverse relationship with the ambient temperature (Mulas et al. 2020), with maximum crack openings corresponding to colder periods, and crack closing during the warmest months, in relation to the thermal retraction-dilatation processes of the facade materials, respectively.

In Fig. 6b, we present the data from the extensometer EXT-1 in the Northwest Gallery (Fig. 4), those obtained by the rod anchored between 10.00 and 10.75 m (long rod) and those obtained by the rod anchored between 2.50 and 3.25 m depth (short rod). These signals show a clearer cyclicality, with a peak to peak amplitude of 0.533 mm for the long rod and 0.723 mm for the short one. We note that during the first year and a half, the long rod showed a relatively static behavior (Fig. 6b), but that after replacing the sensor, its measurements were similar in magnitude and direction to those obtained from the short rod. In both cases, the largest elongation of the rods corresponds to the winter time. This apparently paradoxical behavior can be explained taking into account the offset of the temperature evolution inside the ground. In order to clearly show this evolution, Fig. 7 shows the standardized records of ambient temperature, air temperature at 20 cm depth in the SP1 piezometer (measured by the barometric device) and water temperatures recorded by the CTD-divers in the piezometers SP-1, SP-2, SP-3 and SP-5. This figure clearly shows how there is essentially no noticeable offset between the ambient temperature and the air temperature inside the piezometer, and how the latter is a smoother version of the former. Regarding the piezometers located at the base of the building, Fig. 7 (panels a and b) shows how the water temperatures recorded at depths of 6.1 m and 8.6 m in the piezometers SP-1 and SP-2 exhibit lags of 80 to 106 days with respect to the previous signals, and a clear incidence of the arrival of rainwater in the records. Finally, the CTD-divers located at depths of 19.4 m (SP-3) and 21.7 m (SP-5) in the piezometers of the upper terrace of the building, exhibit lags of 228 and 194 days (Fig. 7c), respectively, in their temperature signals, which are not significantly affected by rainfall water. In this regard, even though the water level recorded by piezometer SP-3 is clearly influenced by the arrival of rainfall waters (Fig. 7a), the location of the CTD-diver in the practically impervious bottom of the piezometer (Uriarte et al. 2020) minimizes its thermal response. These temperature offsets, evidenced through piezometer water, are much larger than those reported by Mulas et al. (2020) in fissure clayey fillings at depths of up to 1 m, and show a complex thermal context in which contraction and dilation processes differentially affect the materials as a function of depth. The final result in extensometer EXT-1 is a practically inverse evolution with respect to the ambient temperature and to some extent directly proportional to the temperature recorded by piezometer SP-3 (Fig. 6b).

Finally, in Fig. 6c we show the records from extensometer EXT-2, located in the "Tholos" (Fig. 5), those corresponding to the rod anchored between 8.00 and 8.75 m (long rod) and those corresponding to the rod anchored between 2.5 and 3.25 m (short rod), together with the temperature evolution recorded in the piezometer SP-5. The displacements show a markedly cyclical behavior, with a peak to peak amplitude of 0.578 mm for the long rod and of 0.380 mm for the short one. The largest elongation is once again recorded during the winter months, with a moderate offset with respect to the signal from extensometer EXT-1, and of the temperature signal recorded by the piezometer SP-5. In any case, an upward trend in the long-term displacement signal of this extensometer can be seen.

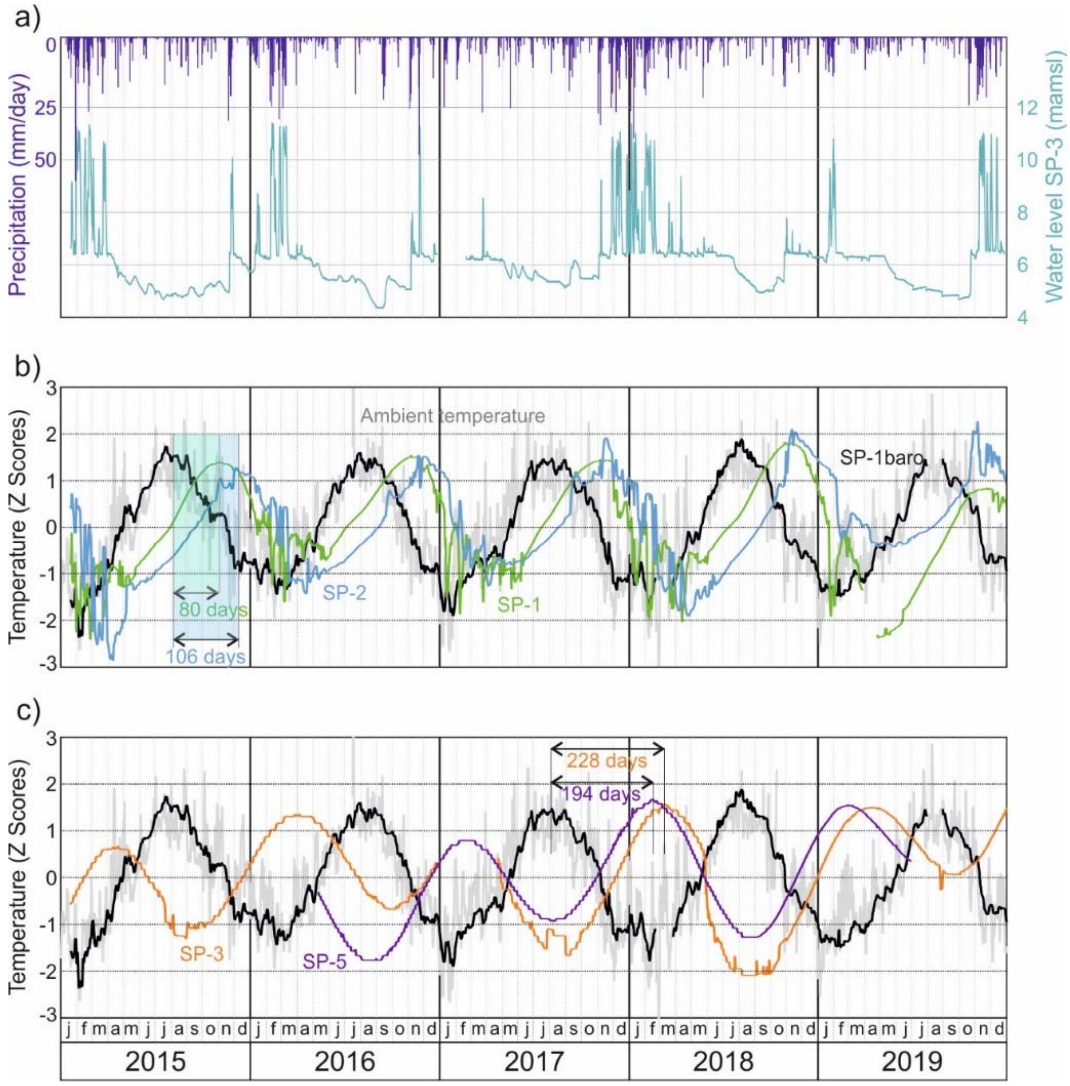


Fig. 7. Hydrometeorological records and temperature evolution inside de rock massif trough piezometers groundwater monitoring: (a) precipitation at Punta Galea meteorological station and groundwater level at piezometer SP-3 (b) comparison between ambient and air temperature recorded at the barometric device placed 20 cm depth in SP-1 and temperatures registered in the piezometers SP-1 and SP-2 (c) comparison with temperatures registered in the piezometers SP-3 and SP-5.

Lomb-Scargle spectral analysis results

Once the displacement records were obtained, discriminating reversible temperature effects from irreversible damaging effects is required (Bottelin et al. 2013; Weber et al. 2017; Mulas et al. 2020). Since our instruments are exposed to the elements, rainfall and winds produce gaps in the registry of the instrumental records (Fig.6). To account for this, we introduce the use of the Lomb-Scargle spectral analysis method to analyze the spectral content of the signals, as this technique is particularly well-suited for the analysis of unevenly sampled time series.

Given the difference in the recording rate of the instruments, we used daily averages in all the analyses. First, before calculating the power spectrum of each signal we did a least-squares linear fit to the raw data. After signal detrending and demeaning, the spectral power analysis allowed us to recognize the most representative periods in the data series. The spectral analysis results along with the phase curves of all the signals are shown in Fig. 8. In Table 1, we show the values of both the linear fits used to detrend the raw data as well as the parameters of the sinusoidal fits derived from the spectral analysis.

As can be seen from Fig. 8, all of the periodograms show a clear peak around 365 days, with spectral peaks between 0.4 and 0.8. These peaks are particularly well defined for the two EXT-1 rods and for the long rod of EXT-2. For the crackmeter signals the peaks are broader due in part to the lowest number of cycles available in the registry as shown in Fig. 6. In addition to this, for the crackmeter CRK-4H and the short rod of extensometer EXT-2, the main peak height is lower due to the large dispersion of the data, as can be seen in the corresponding phase curves. However, for all cases, the annual periodicity derived from the main peak is highly significant. In this sense, the precision with which a peak's period (or frequency) can be identified is directly related to the width of the peak and often the half-width at half-maximum is used (Vanderplas 2018). The peak width would be the inverse of the observational baseline, which is somewhat different for all our signals. The precision of the periods in our periodograms is marked by the shaded vertical region in Fig. 8. The figure also shows the line corresponding to the 5% False-Alarm Probability (FAP) level calculated using the Baluev (2008) method. This is the typical approach to quantify the significance of a peak in a periodogram, as it represents the probability that a series with no signal would lead to a peak of similar magnitude. It gives an estimate of the level that corresponds to a 5% false alarm probability for the largest peak, assuming a null hypothesis of non-varying data with Gaussian noise.

In addition to the clear annual period, there are other peaks that are less significant. At periods shorter than the main annual period, these peaks are a combination of harmonics of the annual signal as well as high-frequency noise. Some others peaks, like the one found around three and a half years present in the EXT-2 spectra are too broad to be significant, despite being above the FAP level, and are associated with periodicities in the signal residuals. Finally, other imprecise peaks, like the one between 1.5 and 2 years in the same EXT-2 spectra would be caused by aliases of the main seasonal signal with periodicities introduced by gaps in the data series.

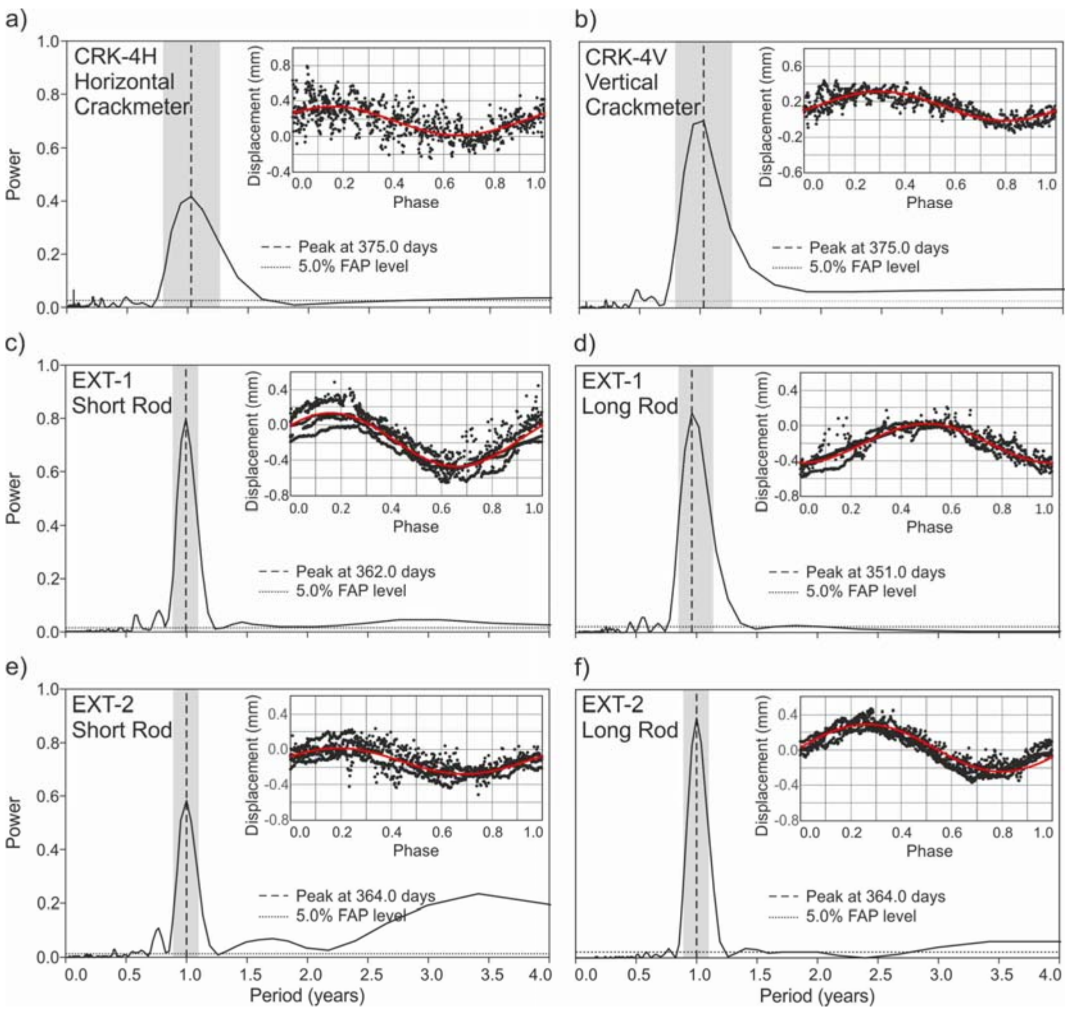


Fig. 8. Periodograms and phase curves for the data series obtained: (a) and (b) horizontal and vertical crackmeters (c) and (d) extensometer EXT-1 short and long rods (e) and (f) extensometer EXT-2 short and long rods.

The values of the main periods (P_{LS} = 1/*f*) derived from this method for the main peaks, range from 364 to 375 days (Table 1). The values of the amplitude (A_f) range from lows of about 0.16 mm in the crackmeter CR-4 to highs of about 0.305 mm in the extensometer EXT-1 long rod. The peak to peak amplitude values ($A_{p\text{-}p}$= 2A_f) are slightly lower to the ones previously derived directly from the experimental data ($A_{p\text{-}p\ exp}$).

Table 1. Parameters of fits to the displacement signals. $P_{LS}(\frac{1}{f})$ is the period determined through power spectrum analysis; A_0 and A_f are the mean value and amplitude of the signals derived from sinusoidal fits to equation (1) above; A_{p-p} is the peak to peak amplitude, obtained as 2A_f, and $A_{p-p\ exp}$ are the values obtained directly from the raw data. The first column (*Lin slope*) shows the slope of the linear fit to the raw data, while the last column (*Lin slope detr*) shows the slope after detrending the sinusoidal fit.

Signal	*Lin slope* (mm/y)	P_{LS} (days)	A_0 (mm)	A_f (mm)	A_{p-p} (mm)	$A_{p-p\ exp}$ (mm)	*Lin slope detr* (mm/y)
CRK-4H	0.05	375	0.174	0.158	0.316	0.566	0.07
CRK-4V	-0.13	375	0.151	0.161	0.322	0.403	-0.09
EXT-1 Short	-0.03	362	-0.167	0.305	0.610	0.723	-0.01
EXT-1 Long	-0.03	351	-0.200	0.223	0.446	0.533	-0.02
EXT-2 Short	0.11	364	-0.133	0.148	0.296	0.380	0.11
EXT-2 Long	0.10	364	0.022	0.269	0.538	0.578	0.12

From this information, we plotted two new sets of figures: Fig. 9, which shows the evolution of the signals before and after removing the linear trend, together with the sinusoidal fits; and Fig. 10, which shows the permanent displacements not explained by the seasonal variation, after removing the sinusoidal trend. With this detrended series further least-squares linear fits were made, whose slopes, as expected, were very close to those obtained from the raw data (Table 1). These complementary figures facilitate the interpretation of the information contained in the records, highlighting the non-reversible component of the signals that informs about the active instability process.

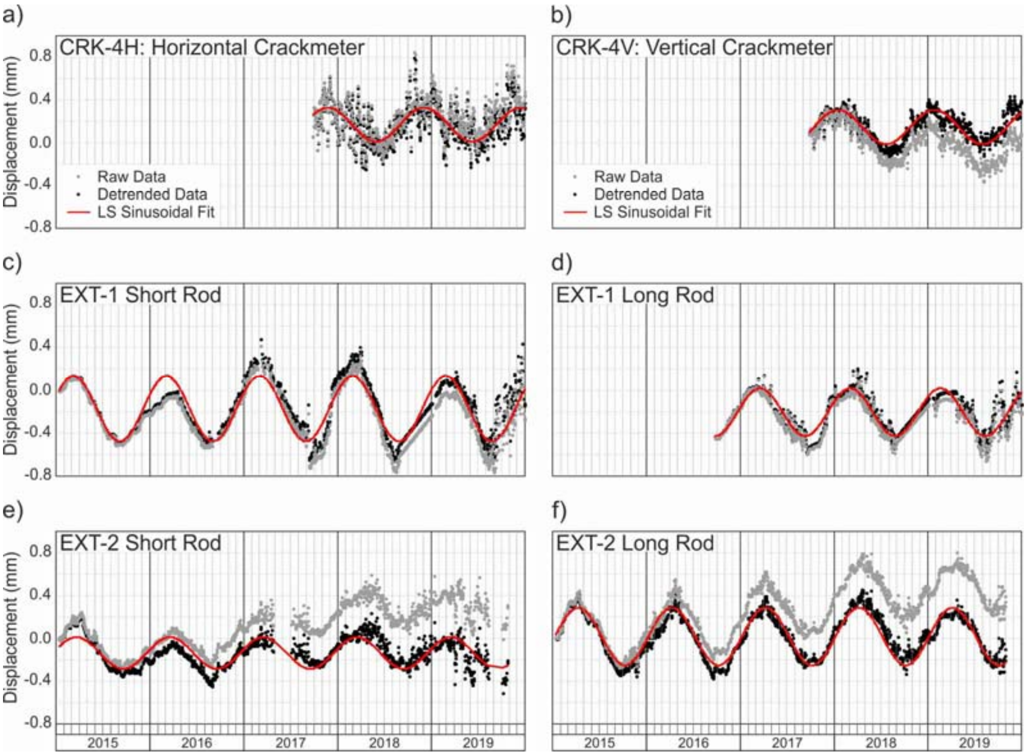


Fig. 9. Raw data (in grey) and detrended data (in black) for the different signals: (a) and (b) horizontal and vertical crackmeters (c) and (d) extensometer EXT-1 short and long rods (e) and (f) extensometer EXT-2 short and long rods. The red line shows the sinusoidal fit to the detrended data with the period found through the spectral analysis.

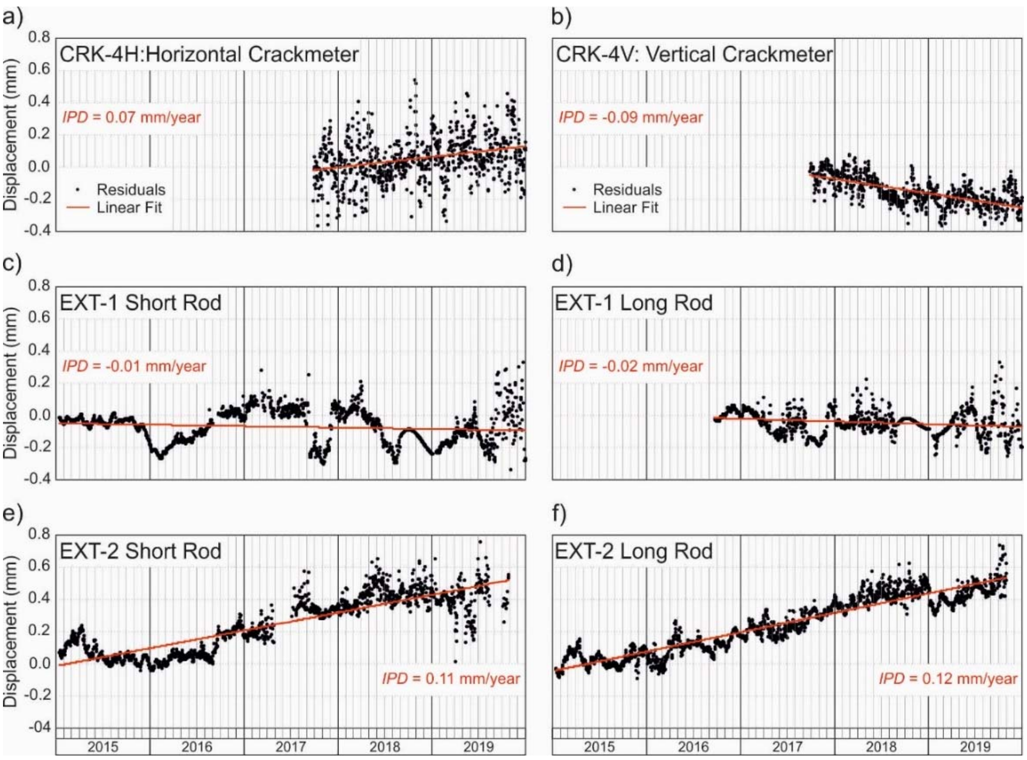


Fig. 10. Residuals after detrending the sinusoidal fit: (a) and (b) horizontal and vertical crackmeters (c) and (d) extensometer EXT-1 short and long rods (e) and (f) extensometer EXT-2 short and long rods. The red line shows the linear fit corresponding to the non-reversible plastic displacement.

Extent of instabilities

Thus, Figs. 9a and b, and more clearly Figs. 10a and b show a slow irreversible trend in the evolution of the façade's main crack monitored in the sector where the Southwest Gallery widens (Fig. 5c). It displays a slight opening of the horizontal crackmeter (0.07 mm/y) and a closing tendency from the vertical one (-0.09 mm/y). Two main things to highlight from these figures are: first, the very low magnitude of the irreversible plastic deformation with respect to the peak-to-peak amplitude of the seasonal displacements, which are slightly over 0.3 mm (Table 1); second, the lack of specific seasonal moments of acceleration in the detrended signals, which show a linear tendency (Fig. 9a, b). Regarding the stability of this sector of the building, the observed trends imply a very slowly sinking and moving outward motion of the outermost element of the southwest façade. This motion is consistent with the slight expansion (0.12 mm/y) recorded by the long rod of extensomenter EXT-3, which is located as shown in Fig. 3; it should be noted, at this point, that its short rod was only functioning during the first year of monitoring (14/06/2016-19/09/2017). Contextualizing all this information into the observations of this sector, the origin of the instability would be in the intermediate pillars that were built directly on the original cliff (Fig. 2f) and more precisely in the intermediate pillar that is located underneath the stairs that give access to the upper terrace (Fig. 5). The greater load of this pillar breaks the superficial stratum locally and produce a slight descending displacement towards the exterior of the building. This motion is jointly transmitted by the concrete structure producing the traction crack in the staircase of the upper terrace (Fig. 5b) and the detachment of the upper part of the facade with respect to the base of the building, which is directly grounded on the underlying terrain. Even though the irreversible component of the displacement is small, it does imply an active plastic deformation, which calls for the need to reinforce the supports of the intermediate pillars. In any case, the rocky massif as a whole is stable, not developing pressure on the structure.

Referring to the data from extensometer EXT-1 it shows a similar tendency for the short and long rods, with a clearly marked seasonal component (Figs. 9c, d). The displacements after removing the cyclic component (Figs. 10c, d) show that there is almost no irreversible plastic deformation since the slopes are barely -0.01 mm/y for the short rod and -0.02 mm/y for the long rod. This behavior, indicative of a stable environment in the Northwest Gallery, is consistent with the rest of the observations in this part of the building, including those from the inclinometer INC-1, which does not show any movement. Regarding the crack found in the top slab, it was determined that this was caused by the careless demolition carried out by a backhoe at the upper entrance to the gallery. Thus, the rocky massif as a whole provides a stable support for the building in this sector.

Finally, the data from extensometer EXT-2 show that the short and long rod follow a similar evolution (Figs. 9e, f). The irreversible plastic displacements, after sinusoidal fit detrending, evidence in this case a clear elongation tendency (Figs. 10e, f) with small but continuous displacement values of 0.11 mm/y for the short rod and 0.12 mm/y for the long rod. Again, it is worth noting the limited amplitude of these movements, compared to the peak-to-peak amplitudes of the seasonal displacements that go from 0.3 mm to slightly over 0.5 mm (Table 1); in addition, after the sinusoidal fit detrending, the signal shows a linear upward trend, without accelerations associated with specific seasonal periods (Fig. 10e, f). The fact that practically all the displacement can be explained by the motion registered in the short rod, which is anchored at a depth between 2.5 and 3.25 m, would indicate that the movement occurs in the outermost environment of the cliff-building complex. Putting into context all the information derived from the observations in this sector, the origin of the instability would be in the different foundation of the "Tholos", whose innermost part is placed directly over the rocky massif, while its outermost part is placed over a cavity and supported only by the perimeter wall of the façade. With this layout (Fig. 11), the load of the outermost columns of this pavilion causes the subsidence and local cracking of the façade wall and the inner concrete slab. The slight downward movement towards the outside recorded by the extensometer is consistent with apertures of the order of 0.12 mm/y recorded in the cracks of this sector. Also, in this case, even though the irreversible component of the displacement was found to be very small, its dynamics prompts to take action aimed at reinforcing the support of the outermost columns of the pavilion. As in the previous sectors, the rock massif is stable and is not in itself the cause of the existing damage.

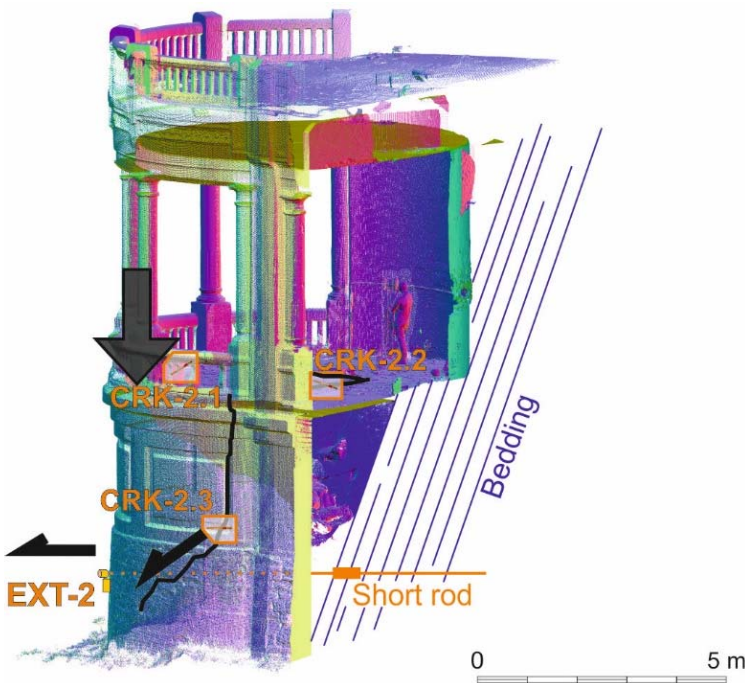


Fig. 11 Movements explanatory diagram at the “Tholos”. Explanation in the text

Discussion

Monitoring issues

The identification, damage assessment, and evaluation of the exposure of cultural heritage sites to geohazards, in order to establish appropriate corrective and conservation measures, is currently a great challenge. To address this challenge, different monitoring techniques including satellite and aerial imagery, satellite and ground based radar interferometry, laser scanning, total station and geotechnical networks have proven to be useful to analyze more and more precisely displacements at different scales, ranging from medium-large site scale to local-scale displacements and structural deformations (e.g. Greif et al. 2006; Roje-Bonacci et al. 2014; Margottini et al. 2015; Janeras et al. 2015; Themistocleous et al. 2018; Dal Cin and Russo 2019).

In the case of extremely slow movements (Greif et al. 2006), geotechnic networks placed on site, allow for continuous monitoring with high precision. In this regard, image-based methods can attain sub millimeter precisions, with an accuracy of 0.5-0.7 mm for GB-InSar (Ferrigno et al. 2017), while the extensometers and crackmeters used in this work have an accuracy of ±0.01 mm (extensometer EXT-1 and EXT-2) to ±0.05 mm (crackmeters CRK-1 to CRK-4) and ±0.1 mm (extensometer EXT-3). The main limitation of these devices is their limited spatial reach (Zhu et al. 2017; Themistocleous et al. 2018), while their main advantage is that they allow for the continuous direct record of displacement in short and long term scales.

Our records show an evident relationship with temperature. In the case of the most superficial devices, crackmeters, the records display reversible opening-closing seasonal movements characteristic of the materials thermal response to ambient temperature variations (Mentes 2012; Colombero et al. 2018). The extensometers, which measure displacements relative to internal points in the rock massif, show a more complex behavior, with the highest elongations occurring cyclically during the coldest months. This evolution would be related to the offset of the temperature signal in the interior of the rock massif (Bottelin et al. 2013; Mulas et al. 2020). In our work, this thermal signal offset has been recognized by the water temperature records of the hydrogeological monitoring piezometers. At this point, a more detailed analysis of these seasonal evolutions would require a specific monitoring system, e.g. by including temperature sensors at different depths in the extensomeric boreholes. In any case these elastic movements are reversible and would not involve destabilization processes by themselves (Greif et al. 2006; Weber et al. 2017; Mulas et al. 2020).

Lomb-Scargle analysis and damage assessment

The removal of these seasonal reversible evolutions is the starting point to characterize often less marked trends of irreversible nature that condition the stability of the cultural heritage site in the medium-long term. For this purpose, we introduce the use of the Lomb-Scargle analysis to identify seasonal trends in geotechnical data series. This analysis, like the one proposed by Mulas et al. (2020) avoids the bias that the consideration of temperature series (Weber et al. 2017) could introduce in the results, and as Vanderplas (2018) points out, it is the optimal statistic for fitting a sinusoidal model to data. Furthermore, an additional advantage of this methodology is that it allows working with unevenly spaced time series, which is a notable advantage given the considerable exposure to the elements of the measurement equipment that in many cases leads to discontinuous series. In our case, all the periodograms obtained from daily data series showed a clearly marked annual cyclical component, with the remaining cyclical components not being statistically significant.

Detrending of the signal with the sinusoidal fit derived from the Lomb-Scargle spectral analysis allows to display ultimately the magnitude and temporal evolution of the irreversible damage. In our work, long-term monitoring of movements in the Punta Begoña Galleries show a clearly differentiated behavior: The Northwest Gallery is stable, while the Southwest Gallery shows evidence of slow continuous displacements in the two monitored sectors, with velocities up to 0.12 mm/y. The small magnitude of these movements, when compared to the seasonal component between 0.3 and 0.5 mm, highlights the need of a continuous monitoring system composed of accurate geotechnical devices. These movements are not related to instability processes of the massif, which appears stable, but to local support problems of the building structure. In addition, the records do not show movement accelerations associated with specific weather events, displaying the residuals a linear tendency.

Overall, the Lomb-Scargle analysis proved to be a particularly well suited tool for the analysis of long term geotechnical records at cultural heritage sites. Its applicability, to analyze and characterize movements in environments where accelerations associated with specific seasonal events (such as snowmelt, freeze-thaw cycles or intense rainfall periods e.g. D'Amato et al. 2016; Frayssines and Hantz 2006; Sandersen et al. 1997) give rise to steps in the signal of residuals remains to be investigated.

Conclusions

The monitoring of long-term structural movements in the most compromised sectors of the Punta Begoña Galleries and the processing of the data series through Lomb-Scargle spectral analysis has allowed us to recognize the nature of damage and its temporal evolution in this building sited on a coastal cliff.

The main advantage of the Lomb-Scargle spectral analysis is that it allows work with unevenly spaced data series to facilitate the identification of periodic components in the signals. From this, it is possible to recognize the role of seasonal patterns in the measurements and to understand the long-term evolution of the series, differentiating reversible elastic movements from irreversible plastic ones.

In our case, it has been possible to distinguish the stable behavior of the Northwest Gallery of the building, contrary to the active dynamics of two sectors of the Southwest Gallery. The limited magnitude of the identified irreversible movements (with a maximum of 0.12 mm/y) underscores the need for long-term monitoring for an adequate contextualization of the information. This information is particularly necessary for the recovery of heritage buildings and natural environments that require interventions that respect their values, avoiding irrecoverable losses (Heinemann 2008; Kyriazi 2019; ICOMOS 2014).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This study has been carried out by the UPV/EHU Research Group IT-1029/16 (Government of the Basque Country) in the framework of the project "Puesta en valor del inmueble histórico cultural Galerías Punta Begoña (Getxo, Bizkaia)" under the cooperation agreement between the University of the Basque Country (UPV/EHU) and the City Council of Getxo (OTRI2016-0738/2019.0318, PES18/97). Finally, the authors are grateful to the editor and the reviewers for the valuable comments that highly improved the paper.

References

Baluev RV (2008) Assessing the statistical significance of periodogram peaks. Mon Not Royal Astron Soc 385:1279-1285. https://doi.org/10.1111/j.1365-2966.2008.12689.x

Bottelin P, Lévy C, Baillet L, Jongmans D, Guéguen P (2013) Modal and thermal analysis of Les Arches unstable rock column (Vercors massif, French Alps). Geophys J Int 194:849-858. https://doi.org/10.1093/gji/ggt046

Casula G, Fais S, Ligas P (2009) An experimental application of a 3-D terrestrial laser scanner and acoustic techniques in assessing the quality of the stones used in monumental structures. Int J Microstruct Mater Prop 4:45-56. https://doi.org/10.1504/IJMMP.2009.028432

Cempel C (2003) Multidimensional condition monitoring of mechanical systems in operation. Mech Syst Signal Proc 17:1291-1303. https://doi.org/10.1006/mssp.2002.1573

Chang PC, Flatau A, Liu SC (2003) Health monitoring of civil infrastructure. Struct Health Monit 2:257-267. https://doi.org/10.1177/1475921703036169

Colombero C, Comina C, Vinciguerra S, Benson PM (2018) Microseismicity of an unstable rock mass: from field monitoring to laboratory testing. J Geophys Res: Solid Earth 123:1673-1693. https://doi.org/10.1002/2017JB014612

Colomina I, Molina P (2014) Unmanned aerial systems for photogrammetry and remote sensing: A review. ISPRS J Photogramm Remote Sens 92: 79-97. https://doi.org/10.1016/j.isprsjprs.2014.02.013

Custance-Baker A, Macdonald S (2014) Conserving concrete heritage, Experts meeting. Meet Rep. The Getty Conservation Institute, Los Angeles

Dal Cin A, Russo S (2019) Evaluation of static and dynamic long-term structural monitoring for monumental masonry structure. J Civ Struct Health Monit 9:169-182. https://doi.org/10.1007/s13349-019-00324-z

Damas Mollá L, Uriarte JA, Aranburu A, Bodego A, Balciscueta U, García Garmilla F, Morales T (2018) Systematic alteration survey and stone provenance for restoring heritage buildings: Punta Begoña Galleries (Basque-Country, Spain). Eng Geol 247:12-26. https://doi.org/10.1016/j.enggeo.2018.10.009

Damas Mollá L, Sagarna Aranburu M, Uriarte JA, Aranburu A, Zabaleta A, García-García F, Antigüedad I, Morales T (2020) Understanding the pioneering techniques in reinforced concrete: the case of Punta Begoña Galleries, Getxo, Spain. Build Res Inf 48:785-801. https://doi.org/10.1080/09613218.2019.1702498

D'Amato J, Hantz D, Guerin A, Jaboyedoff M, Baillet L, Mariscal A (2016). Nat Hazards Earth Syst Sci 16:719-735. https://doi.org/10.5194/nhess-16-719-2016

De Stefano A, Matta E, Clemente P (2016) Structural health monitoring of historical heritage in Italy: some relevant experiences. J Civ Struct Health Monit 6:83-106. http://doi.org/10.1007/s13349-016-0154-y

Díaz Morlán P (1999) Horacio Echevarrieta, 1870–1963: el capitalista republicano. LID Editorial Empresarial, Madrid

Díaz Morlán P (2011) Horacio Echevarrieta, empresario republicano (Bilbainos Recuperados). Muelle de Uribitarte Editores, Bilbao

Ding X, Ren D, Montgomery B, Swindells C (2000) Automatic monitoring of slope deformations using geotechnical instruments. J Surv Eng 126: 2. https://doi.org/10.1061/(ASCE)0733-9453(2000)126:2(57)

Dong Z, Liang F, Yang B, Xu Y, Zang Y, Li J, Wang Y, Dai W, Fan H, Hyyppä J, Stilla U (2020) Registration of large-scale terrestrial laser scanner point clouds: A review and benchmark. ISPRS J Photogramm Remote Sens 163:327-342. https://doi.org/10.1016/j.isprsjprs.2020.03.013

Ferrigno F, Gigli G, Fanti R, Intrieri E, Casagli N (2017) GB-InSAR monitoring and observational method for landslide emergency management: the Montaguto earthflow (AV, Italy). Nat Hazards Earth Syst Sci 17:845–860. https://doi.org/10.5194/nhess-17-845-2017

Frayssines M, Hantz D (2006) Failure mechanisms and triggering factors in calcareous cliffs of the Subalpine Ranges (French Alps). Eng Geol 86:256-270. https://doi.org/10.1016/j.enggeo.2006.05.009

Greif V, Sassa K, Fukuoka H (2006) Failure mechanism in an extremely slow rock slide at Bitchu-Matsuyama castle site (Japan). Landslides 3:22-38. https://doi.org/10.1007/s10346-005-0013-0

Guo Q, Wang X, Zhang H, Li Z, Yang S (2009) Damage and conservation of the high cliff on the Northern area of Dunhuang Mogao Grottoes, China. Landslides 6:89-100. https://doi.org/10.1007/s10346-009-0152-9

Heinemann HA (2008) Why historic concrete buildings need holistic surveys. In: Walraven J, Stoelhorst D (eds) Tailor made concrete structures. Taylor & Francis Group, London, pp 103-108.

Heinemann HA (2013) Historic concrete: From concrete repair to concrete conservation. Dissertation, University of Dortmund. https://doi.org/10.4233/uuid:987fafd0-cd76-4230-be0e-be8843cae08e

Hocke K, Kämpfer N (2009) Gap filling and noise reduction of unevenly sampled data by means of the Lomb-Scargle periodogram. Atmos Chem Phys 9:4197-4206. https://doi.org/10.5194/acp-9-4197-2009

ICOMOS (International Council on Monuments and Sites) (2003) Principles for the analysis, conservation and structural restoration of architectural heritage. ICOMOS 14th General Assembly, Victoria Falls

ICOMOS (International Council on Monuments and Sites) (2010) Illustrated glossary on stone deterioration patterns. ICOMOS International Scientific Committee for Stone, Paris

ICOMOS (International Council on Monuments and sites) (2014). Approaches for the conservation of twentieth century architectural heritage. ICOMOS International Scientific Committee on 20th Century Heritage, Madrid

Janeras M, Jara JA, López F, Marturià J, Royán MJ, Vilaplana JM, Aguasca A, Fàbregas X, Cabranes F, Gili JA (2015) Using several monitoring techniques to measure the rock mass deformation in the Montserrat Massif. International Symposium on Geohazards and Geomechanics. IOP Conf Ser: Earth Environ Sci 26:012030. https://doi.org/10.1088/1755-1315/26/1/012030

Janeras M, Jara JA, Royán MJ, Vilaplana JM, Aguasca A, Fàbregas X, Gili JA, Buxó P (2017) Multi-technique approach to rockfall monitoring in the Montserrat massif (Catalonia, NE Spain). Eng Geol 219:4-20. https://dx.doi.org/10.1016/j.enggeo.2016.12.010

Kyriazi E (2019) Façadism, building renovation and the boundaries of the authenticity. Aesthet Investig 2:184-195. https://doi.org/10.5281/zenodo.4073206

Laborde Marqueze A (2013) COREMANS project: "Criteria for working in stone materials". Ministerio de Educación, Cultura y Deporte, Madrid.

Lomb NR (1976) Least-squares frequency analysis of unequally spaced data. Astrophys Space Sci 39:447-462. https://doi.org/10.1007/BF00648343

Margottini C, Antidze N, Corominas J, Crosta GB, Frattini P, Gigli G, Giordan D, Iwasaky I, Lollino G, Manconi A, Marinos P, Scavia C, Sonnessa A, Spizzichino D, Vacheishvili N (2015) Landslide hazard, monitoring and conservation strategy for the safeguard of Vardzia Byzantine monastery complex, Georgia. Landslides 12: 193-204. https://doi.org/10.1007/s10346-014-0548-z

McKinney W (2010) Data structures for statistical computing in Python. Proc 9th Python Sci Conf. SciPy, Austin, pp 56-61

Mentes G (2012) A new borehole wire extensometer with high accuracy and stability for observation of local geodynamic processes. Rev Sci Instrum 83:015109. https://doi.org/10.1063/1.3676652

Montuori A, Luzi G, Stramondo S, Casula G, Bignami C, Bonali E, Bianchi MG, Crosetto M (2014) Combined use of ground-based systems for Cultural Heritage conservation monitoring. Proc Geosci Remote Sens Symp (IGARSS). IEEE International, Québec, pp 4086-4089. https://doi.org/10.1109/IGARSS.2014.6947384

Morales T, Uribe-Etxebarria G, Uriarte JA, Fernández de Valderrama I (2004) Geomechanical characterisation of rock masses in Alpine regions: the Basque Arc (Basque-Cantabrian basin, Northern Spain). Eng Geol 71:343-362. https://doi.org/10.1016/S0013-7952(03)00160-1

Mulas M, Marnas M, Ciccarese G, Corsini A (2020) Sinusoidal wave fit indexing of irreversible displacements for crackmeters monitoring of rockfall areas: test at Pietra di Bismantova (Northern Apennines, Italy). Landslides 17:231-240. https://doi.org/10.1007/s10346-019-01248-x

Pardo-Igúzquiza E, Rodríguez-Tovar FJ (2011) Implemented Lomb-Scargle periodogram: a valuable tool for improving cyclostratigraphic research on unevenly sampled deep sea stratigraphic sequences. Geo-Mar Lett 31:537-545. https://doi.org/10.1007/s00367-011-0247-x

Pardo-Igúzquiza E, Rodríguez-Tovar FJ (2012) Spectral and cross-spectral analysis of uneven time series with the smoothed Lomb-Scargle periodogram and Monte Carlo evaluation of statistical significance. Comput Geosci 49:207-216. https://doi.org/10.1016/j.cageo.2012.06.018

Park J, Lindberg C, Vernon FL (1987) Multitaper spectral analysis of high-frequency seismograms. J Geophys Res Atmos 921:12675-12684. https://doi.org/10.1029/JB092iB12p12675

Pestiaux P, Berger A (1984) An optimal approach to the spectral characteristics of deep-sea climatic records. In: Berger A, Imbrie J, Hays J, Kukla G, Saltzman B (eds) Milankovitch and Climate. D. Reidel Publ. Co., Dordrecht, pp 417-445.

Press WH, Rybicki GB (1989) Fast algorithm for spectral analysis of unevenly sampled data. Astrophys J 338:277-280. https://doi.org/10.1086/167197

Reback J, the *pandas* development team (2020, March 18) pandas-dev/pandas: Pandas 1.0.3. Zenodo. http://doi.org/10.5281/zenodo.3715232

Roje-Bonacci T, Miščević P, Salvezani D (2014) Non-destructive monitoring methods as indicators of damage cause on Cathedral of St. Lawrence in Trogir, Croatia. J Cult Herit 15:424-431. https://dx.doi.org/10.1016/j.culher.2013.07.008

Rosell J, Cárcamo J (1994) La Fábrica CERES de Bilbao. Los orígenes del hormigón armado y su introducción en Bizkaia. Colegio Oficial de Aparejadores y Arquitectos Técnicos de Bizkaia, Bilbao.

Sandersen F, Bakkehøi S, Hestnes E, Lied K (1997) The influence of meteorological factors on the initiation of debris flows, rockfalls, rockslides and rockmass stability. In: Senneset K (ed) Landslides vol 3: Proc 7th Int Symp Landslides, 3rd edn. AA Balkema, Trondheim, pp 97-114.

Scargle JD (1982) Studies in astronomical time series analysis. II. Statistical aspects of spectral analysis of unevenly spaced data. Astrophys J 263:835–853. https://doi.org/10.1086/160554

Schulz M, Stattegger K (1997) Spectrum: spectral analysis of unevenly spaced paleoclimatic time series. Comput Geosci 23:929-945. https://doi.org/10.1016/S0098-3004(97)00087-3

Tang P, Chen F, Zhu X, Zhou W (2016) Monitoring cultural heritage sites with advanced multi-temporal InSAR technique: the case study of the Summer Palace. Remote Sens 8: 432. https://doi.org/10.3390/rs8050432

Themistocleous K, Danezis C, Frattini P, Crosta G, Valagussa A (2018) Best practices for monitoring, mitigation and preservation of cultural heritage sites affected by geo-hazards: the results of the PROTHEGO project. Sixth International Conference on Remote Sensing and Geoinformation of the Environment. https://doi.org/10.1117/12.2503915

Themistocleous K, Danezis C (2019) Monitoring Cultural Heritage Sites affected by geo-hazards using in situ and SAR data: the Choirokoitia case study. In: Hadjimitsis DG, Themistocleous K, Cuca B, Agapiou A, Lysandrou V, Lasaponara

R, Masini N, Schereier G (eds) Remote Sensing for Archaeology and Cultural Landscapes. Springer, Cham, pp 285-308. https://doi.org/10.1007/978-3-030-10979-0_16

Uriarte JA, Damas Mollá L, Sagarna M, García F, Antigüedad I, Morales T (2020) Characterization of complex groundwater flows in the environment of singular buildings by combining hydrogeological and non-destructive geophysical (ground-penetrating radar) techniques: Punta Begoña Galleries (Getxo, Spain). Hydrol Process 34:1004-1015. https://doi.org/10.1002/hyp.13635

VanderPlas JT, Ivezić Z (2015) Periodograms for multiband astronomical time series. Astrophys J 812:18. https://doi.org/10.1088/0004-637X/812/1/18

VanderPlas JT (2018) Understanding the Lomb-Scargle Periodogram. Astrophys J Suppl Ser 236:16. https://doi.org/10.3847/1538-4365/aab766

Vaughan S, Bailey RJ, Smith DG (2015) Cyclostratigraphy: data filtering as a source of spurious spectral peaks. Geol Soc London Spec Publ 404:151-156. https://doi.org/10.1144/SP404.11

Weber S, Beutel J, Faillettaz J, Hasler A, Krautblatter m, Vieli A (2017) Quantifying irreversible movements in steep, fractured bedrock permafrost on Matterhorn (CH). Cryosph 11: 567-583. https://doi.org/10.5194/tc-11-567-2017

Weedon G (2003) Time-Series Analysis and Cyclostratigraphy: Examining Stratigraphic Records of Environmental Cycles. Cambridge University Press, Cambridge. https://doi.org/10.1017/CBO9780511535482

Zhu H-H, Shi B, Zhang C-C (2017) FBG-based monitoring of Geohazards: current status and trends. Sensors 17, 452. https://doi.org/10.3390/s17030452

4.4. Capítulo IV: Rockfall hazard mitigation in coastal environments by dunes protection: a nature-based solution case on Barinatxe beach (Basque Coast, northern Spain)

Dunas costeras y acantilados en la playa de Barinatxe en Sopela

Jon Ander Clemente, Jesus A. Uriarte, Daniele Spizzichino, Francesco Faccini, Tomás Morales

Engineering Geology

Abstract

Across the world, coastal environments of great landscape, recreational and environmental value are coming under increasing pressure. Within such environments, cliffs are particularly unique and characteristic elements, in which processes of instability develop, and their management requires a transdisciplinary approach that enables the natural condition of the environment to be protected, while at the same time allowing for continued use and enjoyment. In the case of Barinatxe (Basque Coast), the beach evolves into a system of foredunes, flanked by cliffs with frequent rockfall processes. This research analyzes the effect of coastal dunes as an element of natural protection. To this end, and based on a Digital Terrain Model developed by Terrestrial Laser Scanning (TLS) and in situ geological characterization, 3D modeling has been used to analyze rockfall trajectories, evaluating their runout and energy. These models confirm the protective role of coastal dunes, which act as efficient natural barriers against detached rock blocks from cliffs, particularly important in areas where the use of tools based on Nature-Based Solutions (NBSs) guidelines is recommended.

Keywords: coastal dunes, rockfall, Terrestrial Laser Scanner, 3D modeling, Nature-Based solutions (NBSs).

1. Introduction

Rockfall is one of the most frequent and damaging types of mass movement (Rosser and Massey, 2022), common in areas of the world with steep rock slopes and cliffs, both in coastal areas and in inland rock formations (Geertsema and Highland, 2011). In many natural spaces around the world, cliffs have a high landscape and recreational value and attract increasing numbers of visitors. There is therefore a growing need to manage these spaces from the perspective of visitor safety, but also with a view to preserving the environment (Morales et al., 2021). In such contexts, risk avoidance has classically been pursued through interventions such as appropriate land use planning regulations and structural measures such as dikes, mounds, dams and barriers, in order to increase the level of protection (Holub and Hübl, 2008; Accastello et al., 2019). The negative aspects of these measures, such as the high construction and maintenance costs involved and the environmental and aesthetic impact they entail (Godschalk et al., 1999; Touili et al., 2014; Gray et al., 2017), have led to a growing search for less invasive non-structural measures (Li and Eddleman, 2002; Cruz, 2007; Lacambra et al., 2008), combined with prevention, warning and education strategies based on detailed analyses of the terrain (Baum and Godt, 2010; Basher et al., 2015; Morales et al., 2021).

In recent times, there have also been increasing efforts to address environmental, social and economic challenges through what are known as nature-based solutions (NBSs). Although there is a wide range of definitions of NBSs (Sarabi et al., 2019; Solheim et al., 2021), the European Commission (Cecchi, 2015) identifies them as: "Solutions that are inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social and economic benefits and help build resilience. Such solutions bring more, and more diverse, nature and natural features and processes into cities, landscapes and seascapes, through locally adapted, resource-efficient and systemic interventions". A general review of the application of NBSs in urban settings is given in Sarabi et al. (2019), while Solheim et al. (2021) assess the value of implementing NBSs in rural landscapes, by managing vegetation cover and surface waters to reduce impacts from small, frequent events. Specifically in relation to gravitational risks, Accastello et al. (2019) consider protective forests in mountainous areas as a mitigating measure to be integrated into Environmental Risk Management Strategies.

In this context, the aim of this paper is to analyze the role of coastal dunes as natural barriers to control rockfalls and their effectiveness as a nature-based solution to limit risks in coastal environments. Dunes are found along most of the world's coasts (Martínez et al., 2004, Gao et al., 2020), and in Europe alone the total area of coastal dunes has been estimated at over 5,300 square kilometers (Delbaere, 1998, Heslenfeld et al., 2004). These environments often remain relatively stable over time, and in previous works they have been considered as natural solutions against rising sea levels (Sterr, 2008; Pontee et al., 2016; Castelle et al., 2019; Van der Meuler, 2022).

The novelty of our study is that it considers dunes as barriers against gravitational processes. The methodological approach, based on detailed topography, assessment of rockfall dynamics and 3D rockfall modeling, seeks to evaluate the way in which dunes can naturally prevent possible damage caused by these events and the safety implications of the removal of dunes. For this purpose, a real case study has been trialed, framing its characteristics and discussing its role from a risk management perspective. To this end, the Barinatxe beach on the Basque Coast (northern Spain) has been selected. This beach has a dune system developing at the base of the bordering cliffs, which are 35 – 70 m in height and regularly suffer falls of rock fragments. These processes entail a hazard to visitors and users, which need to be managed in a way that respects the geological, environmental and landscape values of the surroundings, making this site particularly suitable for testing our approach.

2. Case study: Barinatxe beach

Barinatxe beach is 755 m long and has an area of about 200,000 square meters at low tide and 61,000 square meters at high tide. It is located on the Cantabrian coast of the Bay of Biscay (Fig. 1), between the municipalities of Getxo and Sopelana, in the of Uribe Kosta region (Basque Country, northern Spain).

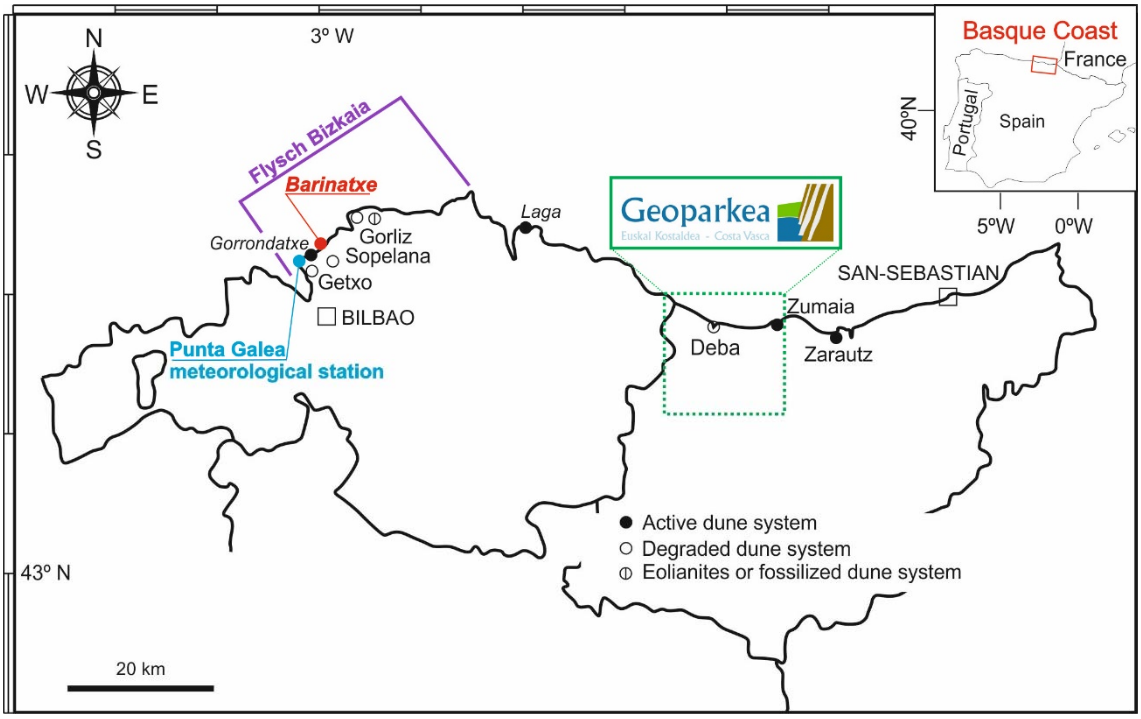


Fig. 1. Geographical location of the study area.

In geological terms (Fig. 2), the region is part of the so-called Basque-Cantabrian basin (Feuillée and Rat, 1971, Ramírez del Pozo, 1973). There, in a basin-bed marine environment, thick sedimentary series were deposited during the Lower Cretaceous - Eocene, characterized by a persistent and well-defined stratification, with great lateral continuity. During the Alpine Orogeny, these materials underwent considerable deformation, giving rise to a mountainous relief that constitutes the western continuation of the Pyrenean mountain range (Baceta et al., 2012).

From a geomorphological perspective, the Basque Coast is generally E-W in orientation (Fig. 1) and is dominated by rocky cliffs with average heights ranging from 20 to 50 meters. In enclaves protected from ocean currents and waves, sandy beaches of moderate extension have developed (Sanjaume et al., 2011, Flor and Flor-Blanco, 2014), generally less than 800 meters in length. From them, and depending on the environmental conditions, dune fields have developed (Cowell and Thom, 1995, Bailey and Bristow, 2004, Provoost et al., 2009, Bateman et al., 2010).

They include active dunes; systems degraded by anthropogenic action; and fossilized dunes (Gallego-Fernández et al., 2011) (Fig. 2).

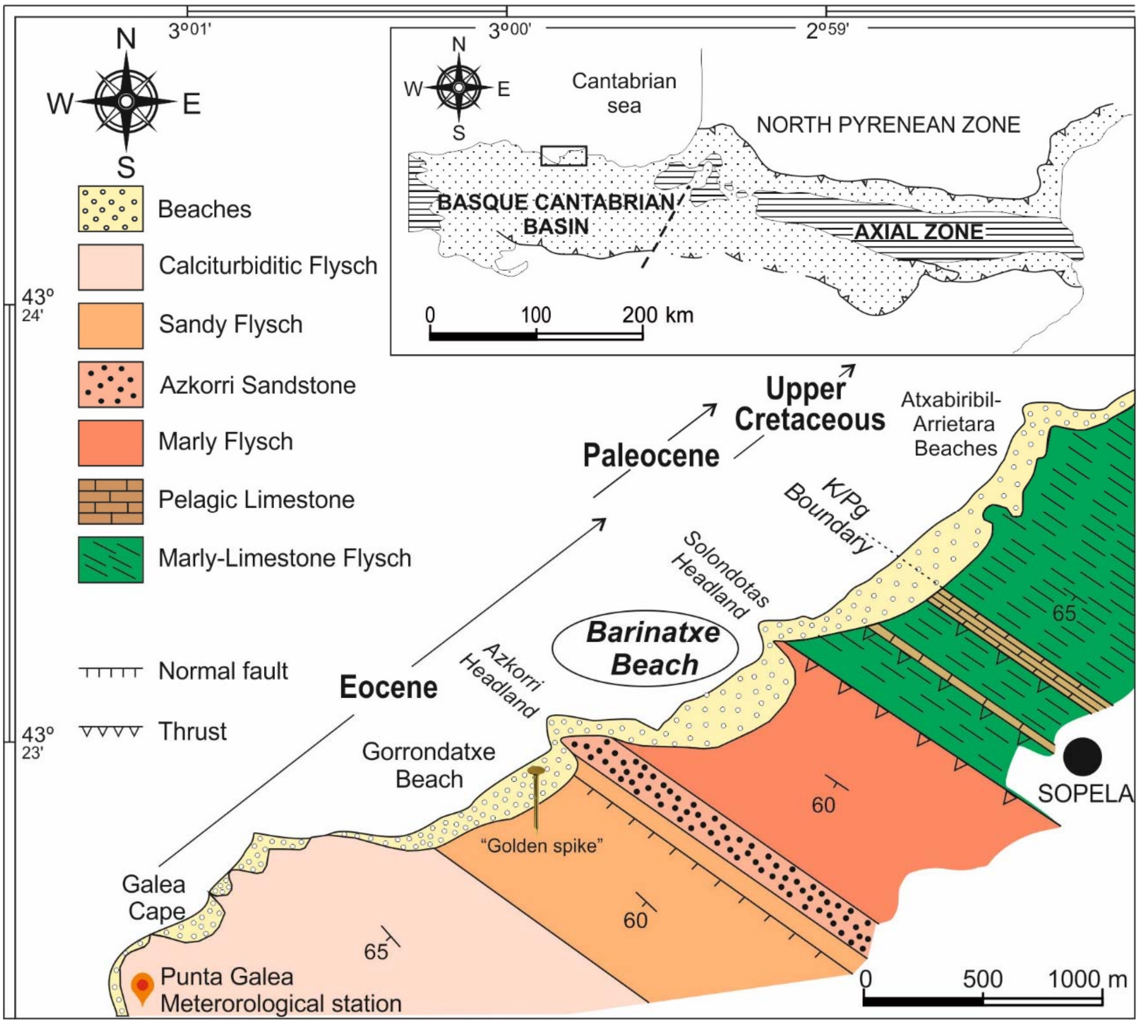


Fig. 2. Sketch map of the main structural features of the Pyrenean belt (modified from Boillot and Capdevila, 1977) and simplified geological map of the Barinatxe beach in the Basque Coast (Bernaola et al., 2009)

In view of the quality and continuity of the coastal outcrops, various recognized areas and protected sites have been created, among them the Basque Coast Geopark, with 2 golden spike marks (Schmitz et al., 2011), and the Bizkaia Flysch, with one golden spike (Payros et al., 2009), evidencing the area's major geological and geomorphological value.

Specifically, the study area forms part of a coastline in which the geological record evolves from Maastrichtian (Upper Cretaceous) to the NE, at Atxabiribil-Arrietara beach (Batenburg et al., 2014; Clemente et al., 2021), to Lutetian (Eocene) to the SW, at Gorrondatxe beach. At Gorrondatxe, the golden spike of the Bizkaia Flysch marks the GSSP (Global Stratotype Section and Point) for the base of the Lutetian Stage (early/middle Eocene boundary; Molina et al., 2011), while at Atxabiribil-Arrietara beach the K/Pg (Cretaceous/Paleogene) boundary is also recognized (Lamolda et al., 1983). Barinatxe beach is located between these two, and the cliffs flanking it show an alternation of marly materials of varying competence ("marly flysch"), from the Ypresian stage (early Eocene; Payros et al., 2007). The materials are arranged in steep dips, a characteristic feature of much of the Basque Coast (Payros et al., 2011). At the base of the cliffs there is a dune system. Since 2008, defensive measures have been taken to protect the dunes against the increasing influx of visitors, especially during the summer season, due to their geomorphological and environmental value.

3. Methods

In this context, the effect of the dunes in relation to the hazard posed by continuous rockfalls from the sea cliffs bordering the beach and the dunes' capacity as a protective natural barrier has been analyzed in the following stages.

3.1. Topographic data

First, detailed topographic information was generated (Fig. 3). Although the environment would, in principle, be an ideal site for use of an Unmanned Aerial Vehicle (UAV), the limitations resulting from the proximity of Bilbao Airport made it more advisable to employ a Terrestrial Laser Scanner (TLS). The equipment used was a FARO Focus 3D X330, which enables objects to be scanned from a distance of up to 330 meters, with an interval error of ±2 mm. Our survey was conducted on March 28, 2021 in the beach area, at 16 points positioned between 150 and 200 meters from the target, allowing us to generate an overall point cloud of the area, comprising 74,459,375 points with an accuracy range of up to 976 kpts/s. It includes GPS for data georeferencing. In our case, all data was georeferenced in accordance to the European Terrestrial Reference System (ETRS89) of the EUREF (Regional Reference Frame Sub-Commission for Europe) (Adam et al., 2002; Bruyninx et al., 2019).

Using the free Cloud Compare v.2.11 software, we were able to modify the point cloud and create the corresponding DTM, for analysis in raster format, by projecting the point cloud perpendicularly onto a flat raster surface, with a cell size of 0.5 m. The software also enabled us to export the original point cloud in other formats, such as ASCII or TXT, which are required for the modeling phase of the research.

The raster was then combined with georeferenced orthophotos in ECW format, obtained from the Geoeuskadi Spatial Data Infrastructure of the Basque Country (www.geoeuskadi.com). These 2021 orthophotos can be modified and adapted to the above information, using the Geographic Information System QGIS 3.6 NOOSA.

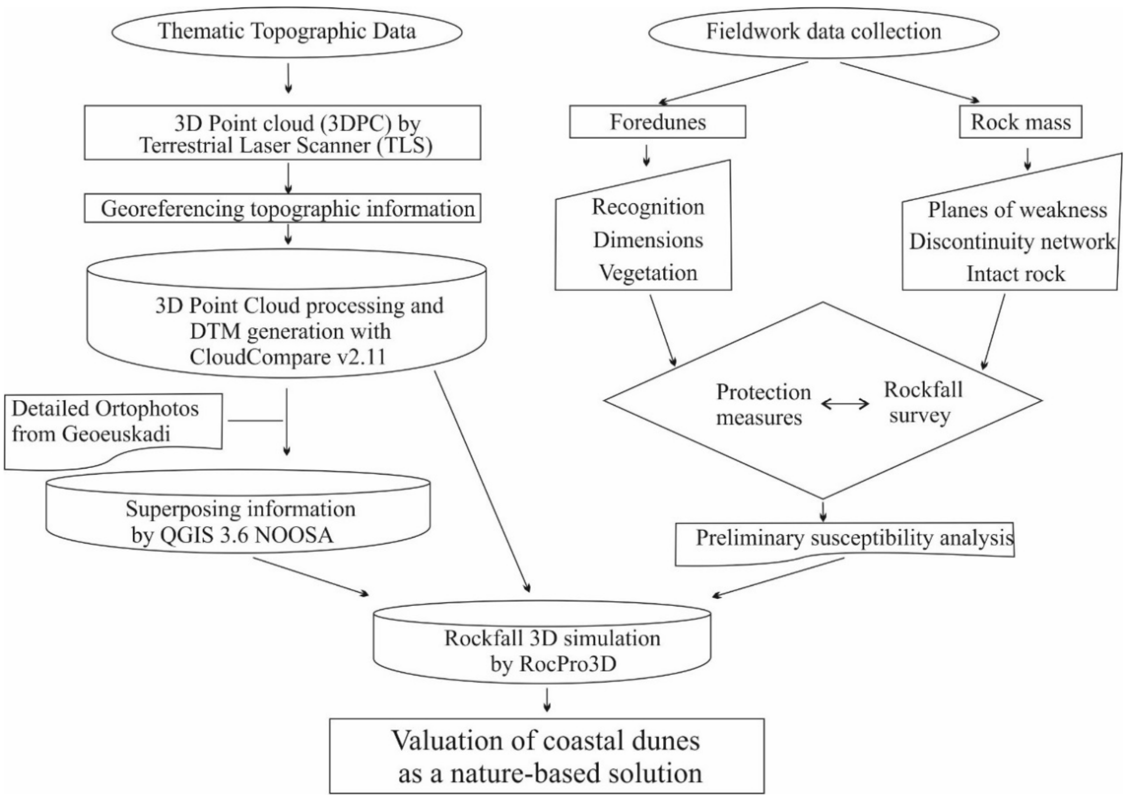


Fig. 3. Methodological flow chart

3.2. Rock mass and dunes survey

In relation to the rock mass, special attention was paid to the network of discontinuities affecting the massif and the nature of its materials. In this regard, the persistence of discontinuities is one of the most limiting factors for the extent of fragmentation (Cai et al., 2004; Kim et al., 2007; Morelli, 2016). Likewise, the main characteristics of the discontinuity families were assessed, including dip and orientation, spacing, persistence, roughness, opening and filling (ISRM, 1978; Bieniawski, 1989; Palmstrom, 2001).

As well as identifying the litology of the intact rock, we also estimated its strength in situ using a Schmidt Hammer (Ulusay, 2015).

Characterization of the rock massif was completed with a determination of the Rock Mass Rating (RMR) as per Bieniawski (1989) and the Geological Strength Index for flyschoid materials as per Marinos and Hoek (2001).

With respect to the dune system, the assessment included identification of materials, origin, degree of development, morphology and typology, relation to external dynamic agents, fundamentally the prevailing winds at the Punta Galea meteorological station (Fig. 1,2), and vegetation coverage.

3.3. Rockfall survey (typology and falling rock fragments characterization)

Bimonthly visits were made for 3 years to record and identify the origin of falls (source areas), typology of failure and trajectory and runout of detached blocks. In this regard, if the network of discontinuities gives rise to the structure of planes of weakness that determine the shape and size of the unstable elements, their orientation with respect to the cliffs determines the failure dynamics (Corominas et al., 2017; Morales et al., 2021). In our work, an analysis of instabilities in stereographic projection was performed using RocScience's Dips.v.6.0 software.

These field surveys established the weight and dimensions of the blocks. In areas in which access was not limited by dune conservation, direct measurements were taken at the foot of the cliffs (weight and volume of fallen blocks) and from scars on the cliff wall (Palmstrom, 2005, Corominas et al., 2017).

These observations were checked against the availability of natural and anthropogenic protective elements as part of the preliminary susceptibility analysis.

3.4. Modeling and rockfall simulation

Using the above information, individualized rockfall simulations were performed with RocPro3D software (RocPro3D, 2018). This software allows a 3D mesh of the study area to be generated from the point cloud created with the Terrestrial Laser Scanner (TLS) with triangulation using the Delaunay method. Through this hybrid model, rockfall simulations can be addressed from a lumped mass approach, as a single material point, or a rigid body approach, accounting for the fragment shape. In our study, we used the rigid body approach, which considers the block impact on the soil surface as a quasi-instantaneous phenomenon during which movement is nil. The main advantage of this software is that it enables 3D simulation of rockfall trajectories, using a probabilistic approximation that considers the variations of block forms, characteristics of soils, and irregularities of the terrain. The impact is characterized by an energy dissipation, taking into account the two restitution coefficients R_n (normal restitution) and R_t (tangential restitution), which are the parameters most commonly used in rockfall studies (Pfeiffer and Bowen, 1989; Chau et al., 2002; Paronuzzi, 2009; Bourrier et al., 2012; Buzzi et al., 2012; Wang et al., 2014; Giokari et al., 2015; Asteriou and Tsiambaos, 2018; Li et al., 2020; Tang et al., 2021).

This processing results in the generation of detailed three-dimensional rockfall simulations, including rockfall trajectories and energies, and the superimposition of orthophotos provides more realistic three-dimensional models.

3.5. Valuation of dunes as an element of natural protection

Once the fall trajectories had been defined, changes in the topography, in relation to the disappearance of the dunes, were entered into the original point cloud using the CloudCompare software and introduced into the RocPro3D program.

Taken together, the runout of the detached rock blocks, the impact energy and the height in both scenarios enabled a detailed assessment to be made of the effect of coastal dunes as a natural retention barrier against detached frock fragments and their role in limiting the negative impact of the instability processes.

4. Results

4.1. Core information on dune system

The Barinatxe dunes are located on a steeply sloping beach with a NE-SW orientation. They consist of fine to medium-sized quartzite sands with fragments of organic origin removed by the wind from the beach foreshore. In this sense, the wind in the area shows a clear NW prevalence, mainly perpendicular to the beach and dunes (Fig.4a), with an average speed of 18.6 km/h (5.16 m/s), exceeding the threshold speed of 5 m/s for the development and preservation of coastal dunes (Sloss et al., 2012). The climate is humid temperate, with an average temperature of 14.8°C and annual rainfall of between 700 and 1,200 mm/year, according to data from the Punta Galea weather station for 2001 - 2019.

Morphologically the dunes are asymmetrical in shape, characterized by a lower slope on the windward side and a steep ramp on the leeward side (Fig. 4a, b and c). On the inland side, the coastal cliff acts as an obstacle to the wind, favoring the development of wind eddies that create a marked depression between the crest of the dunes and the cliff, giving them the character of echo dunes (Tsoar, 1983, 2001). This depression of about 130 meters in length and 5 m in width is maintained over time. Overall, the dune system covers an area of 6,100 m^2, acting as a natural barrier against rockfall from the cliff.

One additional aspect of note is the relatively abundant vegetation growing on the dunes (Fig.4), especially in the summer periods (Fig. 4b), when incipient vegetation develops. This vegetation cover is subsequently destroyed in the erosive phases of winter (Fig. 4c). The flora includes a small population of tree mallow (Lavatera arborea). This species is listed in the Catalogue of Threatened Species of the Basque Country, and as a result, in 2008 a protective perimeter was staked out around the dunes.

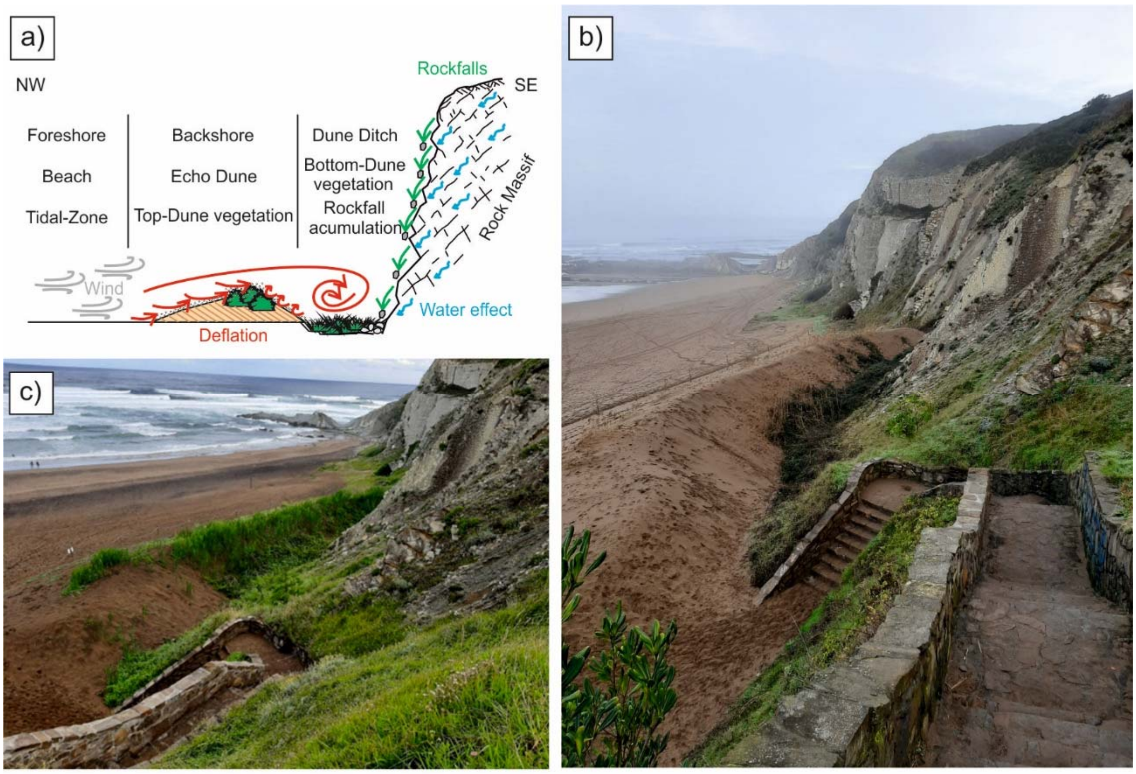


Fig. 4. Dunes of Barinatxe beach: a) conceptual sketch, differentiating beach sectors and depicting the main dynamic processes; b) in winter; c) in summer.

4.2. Characterization of instability processes: rockfalls

The outcrops of flysch sequences in the cliffs show an alternation of marl and marly limestone layers, ranging from a few centimeters to several decimeters in thickness (Fig. 5a), with varying levels of resistance to erosion. The result is an uneven surface with protrusions and indentations at different scales. A Schmidt hammer was used to characterize the strength of both types of materials (360 determinations), giving rebound values (R) of 30 - 40 for the more resistant marly limestones and less than 12 for the marls (Table 1), equivalent to simple compressive strength values (Miller, 1965) of 60 to 80 MPa, in the first case, and less than 20 MPa in the second. These findings coincide with the results of previous studies (Morales et al., 2004).

Fig. 5. Rock mass and instability processes characterization. a) Flyschoid sequence; b) planar instabilities on the main slope on J_1; c) block toppling on the secondary slope over J_2; d) maximum runouts at the northern end of the protected dunes area.

The massif is affected by three principal well-defined joint sets, one running parallel to the bedding planes and the others intersecting it, mainly at right angles. The bedding is the most evident plane of weakness and has the greatest persistence (more than 10 m); it runs perpendicular to the main cliff throughout the environment of the beach, with steep dips to the southwest (S_0: 60/220). The two main joint families, J_1 (45/330) and J_2 (30/100), complete the joint system of the rock mass. These have a much lower persistence, and are mainly limited to the thickness of the strata (less than 1 m). Indeed, these joints appear well developed in the more brittle layers of the interbedded sequence (marly limestones) and tend to terminate at the adjoining marly layers (Fig. 5a), since the distributed deformation within the ductile layer dissipates the stresses at the fracture tip and promotes fracture termination (Cooke et al, 2006; McGinnis et al., 2017). The orientation of the bedding and joints is maintained along the length of the beach.

Table 1. Rock mass characteristics

MATERIALS	**Schmidt rebound number**	**Uniaxial compressive strength (σ_{ci})**	
Marls	6 - 12	10 - 20 MPa	
Marly limestones	30 - 40	60 - 80 MPa	
DISCONTINUITIES	**S_0**	**J_1**	**J_2**
Dip/Dip direction	60/220	45/330	30/100
Spacing	2 - 65 cm	20 - 90 cm	10 - 55 cm
Persistence	> 10 m	< 1 m	< 1 m
Aperture	< 0.1 mm	< 0.1 mm	< 0.1 mm
Roughness (JRC)	Slightly rough (6 - 8)	Smooth (4 - 6)	Smooth (4 - 6)
Infilling	None	Calcite filling < 5 mm	Calcite filling < 5 mm
Weathering	Slightly weathered	Slightly weathered	Slightly weathered
ROCK MASS INDEX			
	RMR	45-50	
	GSI	35-40	

This arrangement results in the detachment of rock blocks of moderate size. The larger blocks come from the thicker calcareous levels (with a maximum thickness of up to 62 cm) and are bounded by the aforementioned joint families which, with usual spacing of 20 to 40 cm for J_1

and 10 to 30 cm for J_2, and maximums of up to 90 and 54 cm respectively, limit and determine their size.

With regard to the instability process, the favorable perpendicular orientation of the bedding causes the detached blocks to evolve on the J_1 plane over the main slope (planar failure, Fig. 5b). In addition, greater erosion of the less resistant marly strata than the more competent strata creates marked indentations that leave the competent strata unsupported, allowing the detached blocks to rotate on their base before falling (toppling failure, Fig. 5c) over secondary slopes perpendicular to the main one.

Figure 6 shows the kinematic analyses by stereographic projection for the main and secondary slopes, evidencing the potential development of planar failure and toppling, respectively (Fig. 6). In the same figure, the main rockfall source areas, trajectories and runout determined in the field surveys are collected (Fig. 5d and 6). The maximum sizes of detached blocks recorded in the accessible areas of the beach are of the order of 0.3 m^3 (7,200 N), which is consistent with the scar volumes observed on the cliff and the maximum spacing of the discontinuities.

4.3. 3D modeling of rockfalls

For the purpose of evaluating the action of the dunes in the rockfall process, the northern part of the beach was selected (Fig. 6), since it includes a sector of protected dunes to the south and a marginal sector to the north, where the dune is poorly developed, in a similar dynamic environment. The lack of construction interventions in this area also facilitates observations of the rock cliff, which in other sectors is limited, e.g. by the existence of a mesh in a large stretch of the access ramp and restricted access in the central area of protected dunes.

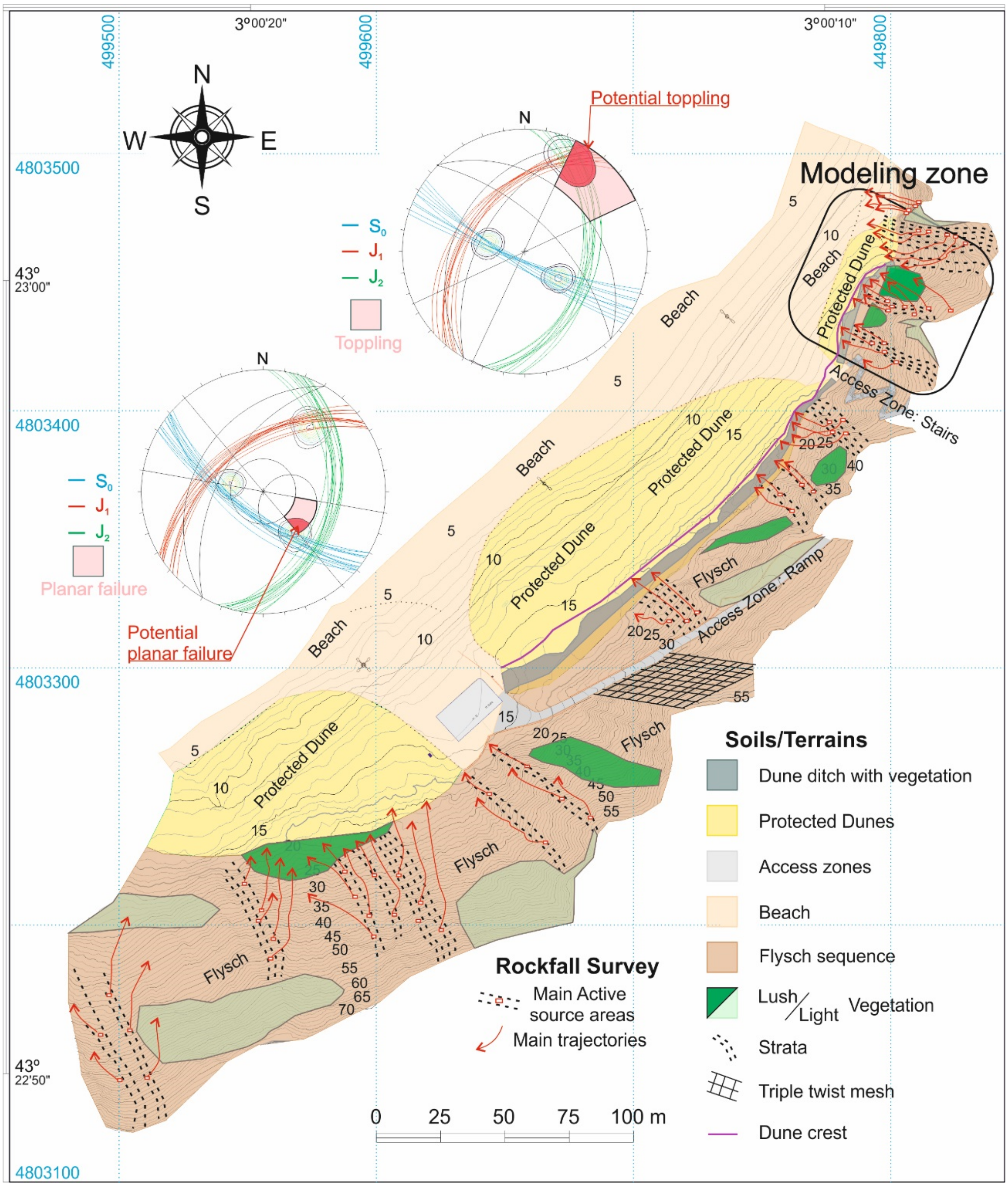


Fig. 6. Differentiation of materials at Barinatxe beach, showing main active source areas and rockfall trajectories. Includes kinematic analysis of the planes of weakness (bedding S_0, joints J_1 and J_2) in stereographic projection (Dips.v.6.0 software, RocScience 2013).

For modeling, the materials were first differentiated and 7 separate terrain types identified according their nature and properties (Fig. 6): sandy beach, sandy dune system; dune ditch, (corresponding to the leeward depression of the dune, which retains continuous vegetation); the flysch sequences; lush cliff grass cover; light cliff grass cover; and anthropized access areas.

Using this differentiation, rebound values were calibrated via 3D back analysis to achieve the best agreement between observations and modeling estimates (Sarro et al., 2018; Fanos and Pradhan, 2019). The values obtained (Table 2) are within the ranges given in the literature for similar materials, from nearly nil to about 0.7 for the normal rebound coefficient and 0.7 to 1 to tangential coefficient (Bourrier et al., 2012; Sarro et al., 2018; Fanos and Pradhan, 2019).

Table 2. Terrain adjusted parameters and random deviations considering Gaussian distributions

MATERIAL PROPERTIES		**Flysch**	**Light vegetation**	**Lush vegetation**	**Sand beach**	**Sand dune**	**Dune ditch**	**Access zone**
Restitution coefficients (R)	*units*							
Mean normal value μ_Rn		0.55	0.45	0.4	0.32	0.35	0.3	0.5
Mean tangential value μ_Rt		0.9	0.85	0.7	0.72	0.65	0.5	0.90
Std.-Dev. σ_R		0.011	0.012	0.012	0.0048	0.016	0.0125	0.011
Limit velocity V_R (lim)	(*m/s*)	10	10	10	10	10	10	10
Limit Std.-Dev. σ_R (lim)		0.0055	0.006	0.006	0.0016	0.012	0.0075	0.0055
Lateral deviation (θh)								
Std.-Dev. σ_θh	(º)	10	5	5	6.25	7.5	8.75	10
Limit velocity V_θh	(*m/s*)	10	10	10	10	10	10	10
Limit Std.-Dev. σ_θh (lim)	(º)	5	2.5	2.5	3.125	3.75	4.355	5
Vertical deviation (θv)								
Std.-Dev. σ_θv	(º)	1	1	1	1	1	1	1
Limit velocity V_θv	(*m/s*)	10	10	10	10	10	10	10
Limit Std.-Dev. σ_θv (lim)	(º)	2	2	2	2	2	2	2
Friction coefficient (k)								
Mean value μ_k		0.45	0.6	0.6	0.6	0.55	0.5	0.45
Std.-Dev. σ_k		0.036	0.045	0.045	0.036	0.045	0.045	0.036
Limit velocity V_k (lim)	(*m/s*)	10	10	10	10	10	10	10
Limit Std.-Dev. σ_k (lim)		0.03	0.03	0.03	0.03	0.03	0.03	0.03

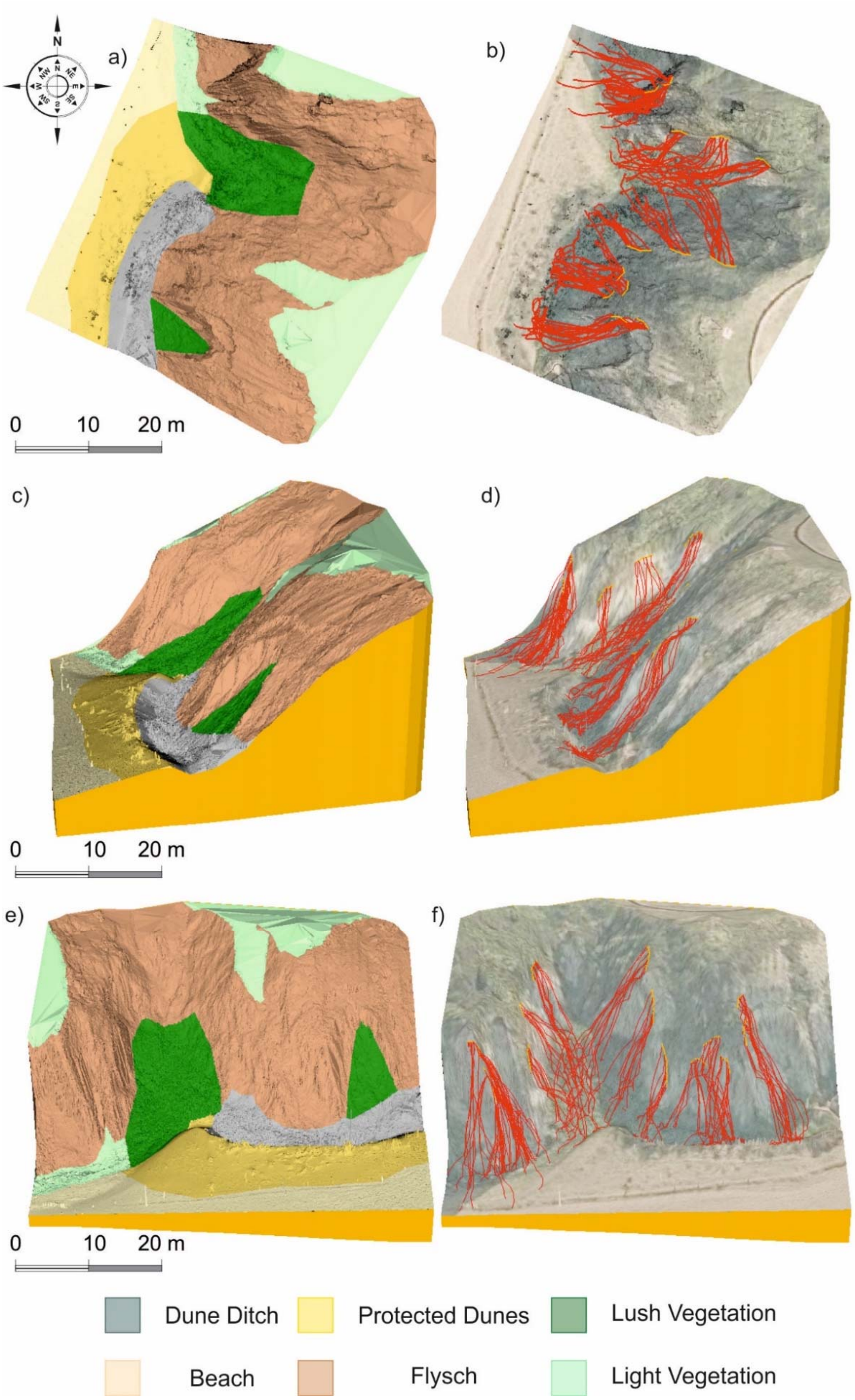


Fig. 7. 3D model showing terrains differentiated and trajectories (red lines) from: zenithal (a and b); profile (c and d) and frontal (e and f) views.

With regard to the results of the modeling, the simulations collected in figure 7 show the trajectories corresponding to the largest volumes indicated in the previous section, as the largest detached blocks constitute the worst case scenario for safety when they remain intact while traveling (Pfeiffer and Bowen, 1989), reaching the highest energy (Sarro et al., 2018; Akin et al., 2021; Morales et al., 2021). To this end, 12 source areas were considered in the study area, from which 270 rockfalls were simulated. The trajectories of the detached blocks on the cliff follow the lines of maximum energy; their progress is limited by two elements: the lush vegetation at the bottom of the depression; and the dune, including the dune ditch. In the first case, the retention is partial and some blocks reach the base of the cliff. In the second case, the retention is total; none of the blocks get past the dune to reach the beach, unlike in the northern sector, where the dune system is poorly developed (Fig. 5d).

In addition, Figure 8 shows the position of the stopping points recorded in the field (Fig. 8a) and those obtained by modeling (Fig. 8b). In both cases, it can be seen that in the southern sector of the modeled area no block get past the crest of the dune and reaches the beach. On the contrary, in the northern sector, where the dune is poorly developed, the blocks reach the beach and even go beyond the delimited protection line. The figure is completed with the information corresponding to the number of trajectories per cell (Fig. 8c), and minimum times of traveling (Fig. 8d).

4.4. Assessment of the protective role of the dune

To evaluate the protective action of the dune, two approaches were used: first, the effect of its disappearance was considered; then, the basic parameters for the sizing of a protective barrier that matches the retention capacity of the dunes were evaluated. In this case, in addition to the runout, another essential parameter to be considered is the energy of the rock blocks along their entire trajectory. In our work, it is especially critical to assess the energy of the blocks arriving the dune.

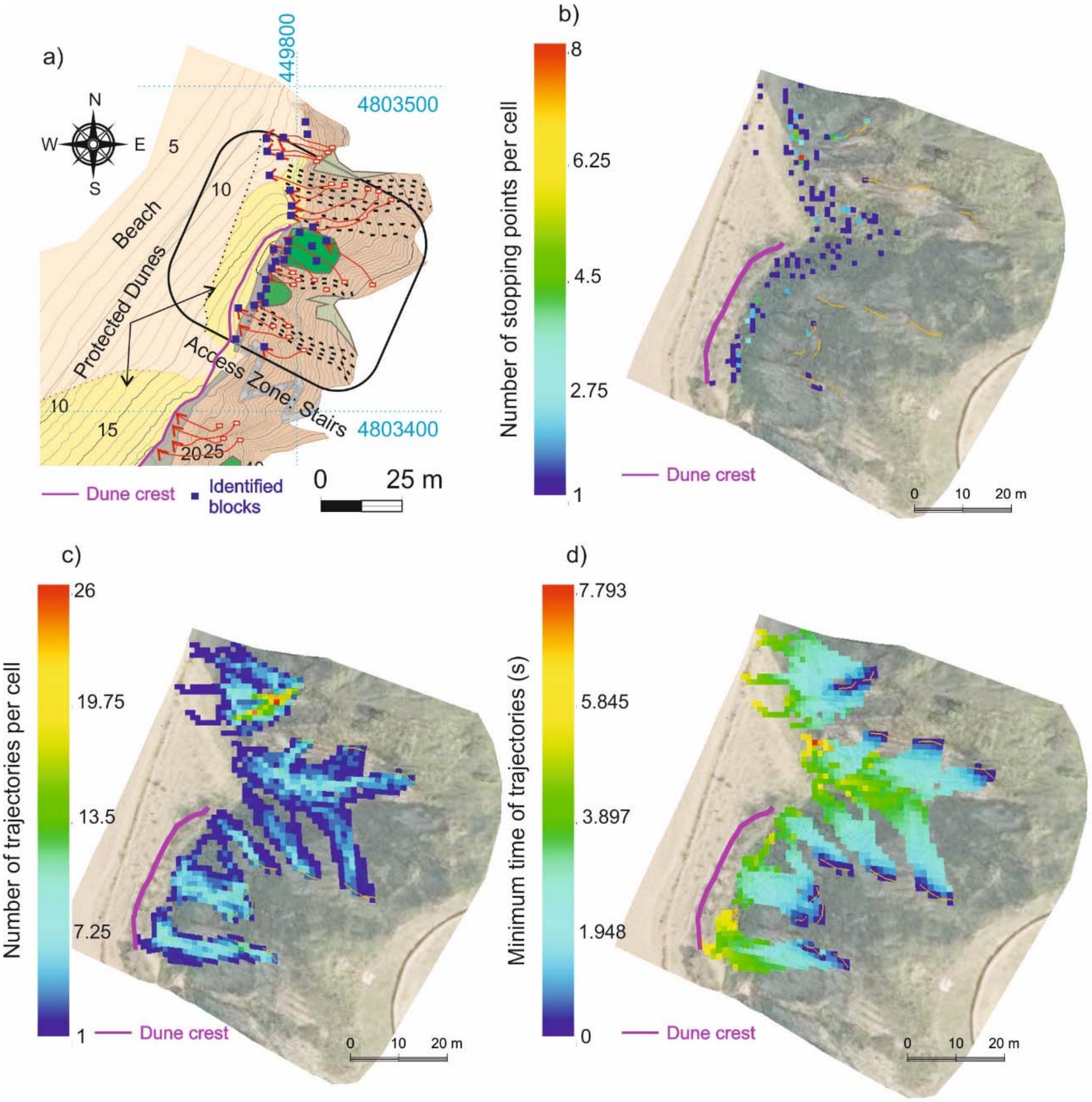


Fig. 8. Analysis of rockfalls; a) fieldwork identification of detached blocks; model results: b) stopping points; c) number of trajectories per cell; and d) minimum time of trajectories.

In the first case, the consideration of dune disappearance was addressed by modifying the original point cloud (Fig. 9a) with Cloud Compare v.2.11 software and creating the corresponding DTM (Fig. 9b and d). As can be seen, the degradation of the dunes would favor some detached blocks to reach the beach, up to distances of 20 m from the base of the cliffs (Fig. 9b), in a situation similar to that already existing at the northern sector of the modeled area (Fig. 8), with the consequent risk for visitors.

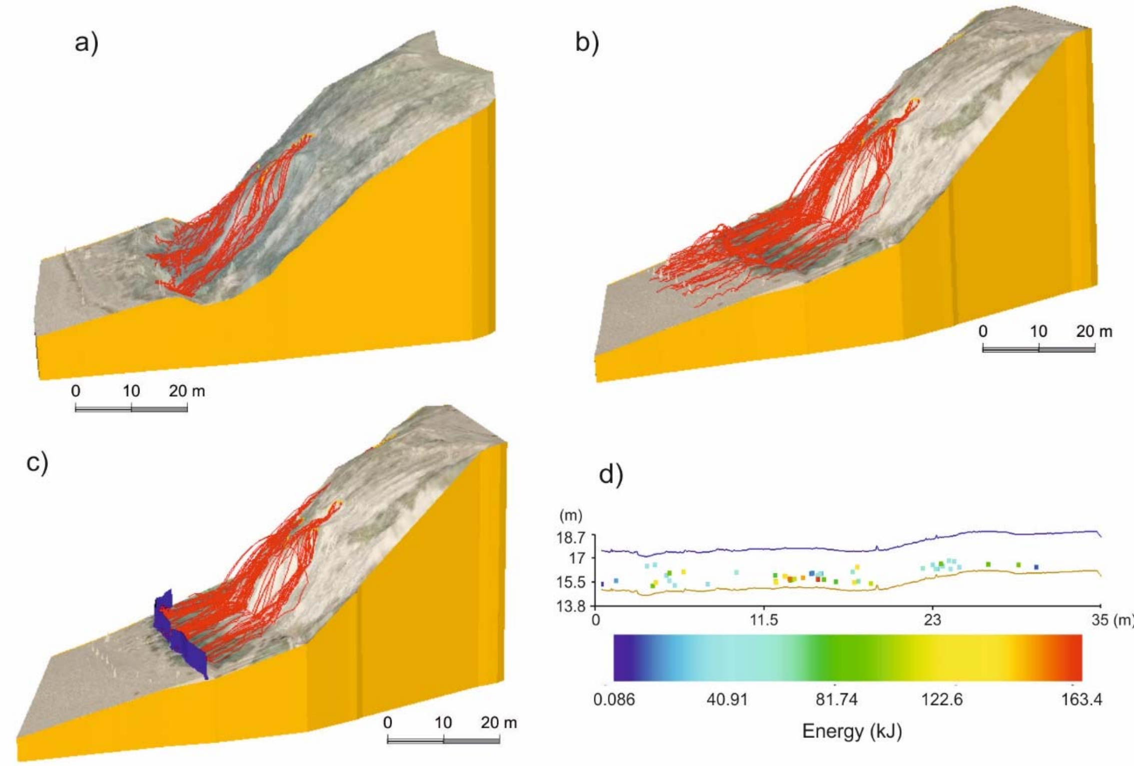


Fig. 9. Evolution of rockfall trajectories: a) in the current situation; b) considering the disappearance of the dunes; c) after the installation of a protection barrier; d) basic parameters for barrier design.

Thus, to avoid the negative effects of the disappearance of the dune, the incorporation of a protective artificial barrier in the 3D model is considered (Fig. 9c and d). In this case, the barrier tool of the RocPro3D software allows analyzing the passage of the detached rocks in the desired vertical profile. The graph in Fig. 9c shows the energies of passage through a profile in the line of the dunes, with a maximum value of 163.4 kJ, and passage heights remaining below 3 m (blue line) above the ground (brown line). These are the basic parameters for the design of a barrier that replaces the protective role that the dune offers naturally, favoring, in addition to safety, conservation and resilience in an environment of high anthropic pressure. In this regard, it should be noted that in the area with protected dunes there has been no record, even in historical registers, the fall of blocks from the cliffs onto the beach open to the public.

In this way, the protection and conservation of the dune is shown as an efficient Nature-Based solution (NBSs) in a space of compromised management.

5. Discussion

Current land management requires the development of innovative approaches that guarantee the conservation of natural spaces and dynamics, and benefit society, mitigating risks and increasing resilience, as stated in the guidelines of the Nature-Based Solutions (NBSs) (Villegas-Palacio et al., 2020, Kumar et al., 2021, Vojinovic et al., 2021, Wu et al., 2021). In this way, previous works have considered the efficiency of these interventions in rural (Solheim et al., 2021), mountainous (Accastello et al, 2019) and coastal (Sterr, 2008; Pontee et al., 2016; Castelle et al., 2019; Van der Meulen, 2022) settings, in the latter case mainly in relation to sea level rise.

This paper introduces the consideration of coastal dunes as natural barriers to control rockfalls and their contribution in coastal adaptation strategies. For this purpose, the effectiveness of the Barinatxe dune system in reducing the impacts of small and frequent rockfalls (extensive hazards) from the surrounding coastal cliffs is evaluated, as a pilot experience that can be extrapolated to larger environments.

Rockfall process was approached by 3D modeling. 3D numerical models allows including geometrical and dynamic effects of the 3D topography, taking into account the lateral dispersion in the generation of 3D trajectories (Sarro et al., 2018; Fanos and Pradhan, 2019), thus overcoming the limitations of 2D models (Volkwein et al., 2011). In our work, a detailed digital terrain model obtained by TLS with a precision of +-2 mm is included in RocPro3D software (RocPro3D, 2018).

As input information for modeling, the typology, frequency and entity of rockfall events was addressed by field surveys conducted over 3 years and completed with historical information

(Bunce et al., 1997; Hungr et al., 1999; Copons et al., 2009). The size of detached blocks, which is one of the main decisive factors controlling their fall path (Hungr et al., 1999; Okura et al., 2000; Erismann and Abele, 2001; Corominas et al., 2017; Sarro et al., 2018), is defined by the thickness of the most competent rock strata and the persistence and separation of the discontinuity families (Cai et al., 2004; Kim et al., 2007; Morelli, 2016), reaching volumes of up to 0.3 m^3, which is consistent with the maximum separation of discontinuities and coincides with the dimensions of the scars on the cliff. The activity of the source areas is determined by the favorable orientation of the stratification with respect to the slope, so instabilities are limited to moderate detachments on J_1, with an inclination of 45^0, and more complex toppling processes on J_2, with only 30º tilt, on the secondary slopes. Thus, the kinematic approach is shown as an essential requirement in the identification of source areas activity, both by direct assessment or image processing (Riquelme et al., 2018; Sarro et al., 2018; Albarelli et al., 2021).

From this information, after calibrating the 3D model, we proceeded to carry out simulations in 3 scenarios corresponding to the current situation of the dunes, the situation corresponding to the disappearance of the dunes and the needs for action resulting from their degradation. Modeling focuses on the larger rock blocks previously established, as they constitute the worst case scenario for safety when remain intact while traveling down slope (Pfeifer and Bowen, 1989;), reaching the highest energy (Corominas et al., 2017; Morales et al., 2021). Referring to the materials in the slope, 7 types of terrains with clearly different mechanical responses were considered. Results were ground-truthed with field observations. In any case, this item presents field of improvement, since the characteristic parameters of materials were obtained through adjustment, and additional experimental determinations in the field and laboratory (Bourrier et al., 2012; Asteriou and Tsiambaos, 2016, 2018; Ji et al., 2020) will enable us to verify and refine the results.

The approach tested at Barinatxe beach, verifies the efficiency of dune systems as a reasonable natural solution to avoid risks related with rockfall. Dunes limit the evolution of the blocks that reach the beach, in no case exceeding the crest of the dune. On the contrary, it is noted that not preserving the dunes would allow the blocks to reach distances of 20 m in the most frequented area of the beach, according to the 3D modeling; a fact that is confirmed by the observations in the northern sector of the modeled area where the dunes end. This situation introduces a risk that could be avoided by preserving the dunes or building a 3 m high protective barrier capable of withstanding energies of up to163.4 kJ, which would have a significant impact on the environmental, ecological and landscape value of the beach, causing a negative public perception (Touili et al., 2014; Gray et al., 2017). In this sense, the future application of nature-based solutions (NBSs) in coastal adaptation management seeks to take advantage of the local natural elements and processes from small-scale to large-scale (Van der Meulen et al., 2022) to harness the forces of nature for the benefit of society.

6. Conclusions

This work allows to verify the protective role of coastal dunes as natural barriers against the risk of rockfall from coastal cliffs. Thus, their protection and conservation are shown to be an effective strategy that can be integrated into the framework of nature-based solutions (NBSs).

The methodology, based on a Digital Terrain Model developed by Terrestrial Laser Scanning (TLS), in situ geological characterization and 3D modeling, has been tested in Barinatxe beach, proving to be adequate to evaluate the trajectory, energy and runout of rockfalls. From this, detailed 3D models allow analyzing the effect of the dunes on the rockfall evolution and to assess the impact of their disappearance on beach safety.

The dunes have proven to be an effective natural barrier that prevents the rockfalls from reaching the beach area open to the public. In this way, the conservation of the dunes returns to us, in the form of safety, the endeavor of protecting these natural elements of high geomorphological, ecological and environmental value.

Acknowledgements

This study has been carried out by the UPV/EHU Research Group IT-1682/22 (Government of the Basque Country) in the framework of the strategic project “Analysis of instabilities in coastal environments of the Basque Country” PES-18/97 (University of the Basque Country). Finally, the authors are grateful to the reviewers and the handling editor, for the valuable comments that highly improved the paper.

References

Accastello, C., Blanc, S., Brun, F., 2019. A framework for the integration of Nature-Based Solutions into environmental risk management strategies. Sustainability 11, e489. https://doi.org/10.3390/su11020489.

Adam, J., Augath, W., Boucher C., Bruyninx, C., Caporali, A., Gubler, E., Gurtner, W., Habrich, H., Harsson, B.J., Hornik, H., Ihde, J., Kenyeres, A., Marel, H.V.D., Seeger, H., Simek, J., Stangl, G., Torres, J.A., Weber, G., 2002. Status of the European reference frame – EUREF. IAG Symp. Ser. 125, 42–46. https://doi.org/10.1007/978-3-662-04709-5_8.

Akin, M., Dinçer, I., Ok, A.O., Orhan, A., Akin, M.K., Topal, T., 2021. Assessment of the effectiveness of a rockfall ditch through 3-D probabilistic simulations and automated image processing. Eng. Geol. 283, e106001. https://doi.org/10.1016/j.enggeo.2021.106001.

Albarelli, D.S.N.A, Mavrouli, O.C., Nyktas, P, 2021. Identification of potential rockfall sources using UAV-derived point cloud. Bull. Eng. Geol. Environ. 80, 6539–6561. https://doi.org/10.1007/s10064-021-02306-2.

Asteriou, P., Tsiambaos, G., 2016. Empirical model for predicting rockfall trajectory direction. Rock Mech. Rock Eng. 49, 927–941. https://doi.org/10.1007/s00603-015-0798-7.

Asteriou, P., Tsiambaos, G., 2018. Effect of impact velocity, block mass and hardness on the coefficients of restitution for rockfall analysis. Int. J. Rock. Mech. Min. Sci. 106, 41–50. https://doi.org/10.1016/j.ijrmms.2018.04.001.

Baceta, J.I., Orue-Etxebarria, X., Apellaniz, E., Martín-Rubio, M., Bernaola, G., 2012. El Flysch del litoral Deba-Zumaia: una “ventana” a los secretos de nuestro pasado geológico. Servicio Editorial de la Universidad del País Vasco, Bilbao.

Bailey, S.D., Bristow, C.S., 2004. Migration of parabolic dunes at Aberffraw, Anglesey, north Wales. Geomorphology 59, 165–174. https://doi.org/10.1016/j.geomorph.2003.09.013.

Basher, L., Harrison, D., Philips, C., Marden, M., 2015. What do we need for a risk management approach to steepland plantation forests in erodible terrain. N. Z. J. For. 60, 7–10.

Bateman, M.D., Carr, A.S., Dunajko, A.C., Holmes, P.J., Roberts, D.L., McLaren, S.J., Bryant, R.G., Marker, M.E., Murray-Wallace, C.V., 2010. The evolution of coastal barrier systems: a case study of the Middle-Late Pleistocene Wilderness barriers, South Africa. Quat. Sci. Rev. 30, 63–81. https://doi.org/10.1016/j.quascirev.2010.10.003.

Batenburg, S.J., Gale, A.S., Sprovieri, M., Hilgen, F.J., Thibault, N., Boussaha, M., Orue-Etxebarria, X., 2014. An astronomical time scale for the Maastrichtian based on the Zumaia and Sopelana sections (Basque Country, northern Spain). J. Geol. Soc. 171, 165–180 https://doi.org/10.1144/jgs2013-015.

Baum, R.L., Godt, J.W., 2010. Early warning of rainfall-induced shallow landslides and debris flows in the USA. Landslides 7, 259–272. https://doi.org/10.1007/s10346-009-0177-0.

Bernaola, G., Martín-Rubio, M., Baceta, J.I., 2009. New high resolution calcareous nannofossil analysis across the Danian/Selandian transition at the Zumaia section: comparison with South Tethys and Danish Sections. Geol. Acta. 7, 79–92. https://doi.org/10.1344/105.000000272.

Bieniawski, Z.T., 1989. Engineering Rock Mass Classifications: A complete manual for engineers and geologists in mining, civil and petroleum engineering. John Wiley & Sons, New York.

Boillot, G., Capdevila, R., 1977. The Pyrenees: Subduction and collision. Earth Planet. Sci. Lett. 35: 151–160. https://doi.org/10.1016/0012-821X(77)90038-3.

Bourrier, F., Berger, F., Tardig, P., Dorren, L., Hungr, O., 2012. Rockfall rebound: comparison of detailed field experiments and alternative modelling approaches. Earth Surf. Process. Landforms 37, 656–665. https://doi.org/10.1002/esp.3202.

Bruyninx, C., Legrand, J., Fabian, A., Pottiaux, E., 2019. GNSS metadata and data validation in the EUREF Permanent Network. GPS Solut. 23, e106. https://doi.org/10.1007/s10291-019-0880-9.

Bunce, C.M., Cruden, D.M., Morgenstern, N.R., 1997. Assessment of the hazard from rock fall on a highway. Can. Geotech. J. 34, 344–356. https://doi.org/10.1139/t97-009.

Buzzi, O., Giacomini, A., Spadari, M., 2012. Laboratory investigation on high values of restitution coefficients. Rock Mech. Rock Eng. 45, 35–43. https://doi.org/10.1007/s00603-011-0183-0.

Cai, M., Kaiser, P.K., Uno, H., Tasaka, Y., Minami, M., 2004. Estimation of rock mass deformation modulus and strength of jointed hard rock masses using the GSI system. Int. J. Rock Mech. Min. Sci. 41: 3–19. https://doi.org/10.1016/S1365-1609(03)00025-X.

Castelle, B., Laporte-Fauret, Q., Marieu, V., Michalet, R., Rosebery, D., Bujan, S., Luban, B., Bernard, J.P., Valance, A., Dupont, P., Oul El Moctar, A., Narteau, C., 2019. Nature-based solution along high-energy eroding sandy coasts: Preliminary tests on the resinstatement of natural dynamics in reprofiled coastal dunes. Water 11, e2518. https://doi.org/10.3390/w11122518.

Cecchi, C., 2015. Towards an EU Research and Innovation Policy Agenda for Nature-Based Solutions & Re-Naturing Cities: Final Report of the Horizon 2020 Expert Group on Nature-Based Solutions and Re-Naturing Cities. Directorate-Generale for Research and innovation, European Commission: Brussels, Belgium, 2015. https://doi.org/10.2777/479582.

Chau, K.T., Wong, R.H.C., Wu, J.J., 2002. Coefficient of restitution and rotational motions of rockfall impacts. Int. J. Rock Mech. Min. Sci. 39, 69–77. https://doi.org/10.1016/S1365-1609(02)00016-3.

Clemente, J.A., Uriarte, J.A., Apraiz, A., Morales, T., 2021. Modelización de caída de rocas en los acantilados carbonatados “tipo flysch” de la playa de Atxabiribil (Sopela, Bizkaia): análisis tridimensional. Rev. Soc. Geol. Esp. 34, 52–63.

Cooke, M.L., Simo, J.A., Underwood, C.A., Rijken, P., 2006. Mechanical stratigraphic controls on fracture patterns within carbonates and implications for groundwater flow. Sediment. Geol. 184, 225–239. https://doi.org/10.1016/j.sedgeo.2005.11.004.

Copons, R., Vilaplana, J.M., Linares, R., 2009. Rockfall travel distance analysis by using empirical models (Solà d'Andorra la Vella, Central Pyrenees). Nat. Hazards Earth Syst. Sci. 9, 2107–2118. https://doi.org/10.5194/nhess-9-2107-2009.

Corominas, J., Mavrouli, O., Ruiz-Carulla, R., 2017. Rockfall ocurrence and fragmentation, in: Sassa, K., Mikoš, M., Yin, Y. (Eds), Advancing culture of living with landslides. Springer, Cham, pp. 75–97 https://doi.org/10.1007/978-3-319-59469-9_4.

Cowell, P.J., Thom, B.G., 1995. Morphodynamics of coastal evolution, in: Carter R.W.G., Woodroffe, C.D. (Eds), Coastal Evolution, Late Quaternary Shoreline Morphodynamics. Cambridge University Press, Cambridge, pp. 33–86.

Cruz, A.M., 2007. Engineering contribution to the field of emergency management, in: McEntire, D.A. (Ed.), Disciplines, Disasters and Emergency Management: The Convergence and Divergence of Concepts, Issues and Trends from the Research Literature. C. C. Thomas, Springfield, pp. 49–60.

Delbaere, B.C.W., 1998. Facts and figures on European biodiversity; state and trends 1998-1999. European Centre of Nature Conservation, Tilburg.

Erismann, T.H., Abele, G., 2001. Dynamics of Rockslides and Rockfalls. Springer, Berlin.

Fanos, A.M., Pradhan, B., 2019. A novel rockfall hazard assessment using laser scanning data and 3D modelling in GIS. Catena 172, 435–450. https://doi.org/10.1016/j.catena.2018.09.012.

Feuillée, P., Rat, P., 1971. Structures et paléogéographies pyrénéo-cantabriques, in: Debyser, J., Le Pichon, X., Montardet, L. (Eds.), Histoire structural du Golfe de Gascogne, Tome 2. Publ. l'Inst. Français Pétrole Coll. et Sémin., Technip., Paris : 1–48.

Flor, G., Flor-Blanco, G., 2014. Componentes de viento generadores de morfologías y campos dunas de costeras en Asturias. Cuaternario y Geomorfol. 28, 47–68.

Gallego-Fernández, J.B., Sánchez, I.A., Ley, C., 2011. Restoration of isolated and small coastal sand dunes on the rocky coast of northern Spain. Ecol. Eng. 37, 1822–1832. https://doi.org/10.1016/j.ecoleng.2011.06.017.

Gao, J., Kennedy, D.M., Konlechner, T.M., 2020. Coastal dune mobility over the past century: A global review. Prog. Phys. Geogr. 44, 814–836. https://doi.org/10.1177/0309133320919612.

Geertsema, M., Highland, L.M., 2011. Landslides: Human Health Effects. Encyclopedia Environ. Health: 380–395. https://doi.org/10.1016/B978-0-444-52272-6.00550-X.

Giokari, S., Asteriou, P., Saroglou, C., Tsiambaos, G., 2015. Rockfalls: Effect of slope surface weathering on the coefficients of restitution, in: Lollino, G., Giordan, D., Crosta, G.B., Corominas, J., Azzam, R., Wasowski, J., Sciarra, N (Eds.), Engineering Geology for Society and Territory, Volume 2. Springer International Publishing, Switzerland, pp. 2041-2044. https://doi.org/10.1007/978-3-319-09057-3_363

Godschalk, D.R., Beatley, T., Berke, P., Brower, D.J., Kaiser, E.J., 1999. Natural Hazard Mitigation: Recasting Disaster Policy and Planning. Island Press, Washington D.C.

Gray, J.D.E, O'Neill, K., Qiu, Z., 2017. Coastal residents' perceptions of the function of and relationship between engineered and natural infrastructure for coastal hazard mitigation. Ocean Coast. Manag. 146: 144–156. https://doi.org/10.1016/j.ocecoaman.2017.07.005.

Heslenfeld, P., Jungerius, P.D., Klijn, J.A., 2004. European Coastal Dunes: ecological values, threats, opportunities and policy development, in: Martínez, M.L., Psuty, N.P. (Eds.), Coastal Dunes: Ecology and Conservation. Ecological Studies 171, Springer-Verlag, Berlin, pp. 335-351.

Holub, M., Hübl, J., 2008. Local protection against mountain hazards – state of the art and future needs, Nat. Hazards Earth Syst. Sci. 8, 81–99. https://doi.org/10.5194/nhess-8-81-2008.

Hungr, O., Evans, S., Hazzard, J., 1999. Magnitude and frequency of rockfalls and rock slides along the main transportation corridors of south-western British Columbia. Can. Geotech. J. 36, 224–238. https://doi.org/10.1139/t98-106.

ISRM (International Society for Rock Mechanics), 1978. Suggested methods for the quantitative description of discontinuities in rock masses. Int. J. Rock Mech. Mining Sci. & Geomech. Abstr. 15, 319–368.

Ji, Z.-M., Chen, Z.-J., Niu, Q.-H., Wang, T.-H., Wang, T.-J., Chen, T.-L., 2020. A calculation model of the normal coefficient of restitution based on multi-factor interaction experiments. Landslides 18, 1531–1553. https://doi.org/10.1007/s10346-020-01556-7.

Kim, B.H., Cai, M., Kaiser, P.K., Yang, H.S., 2007. Estimation of block sizes for rock masses with non-persistent joints. Rock Mech. Rock Eng. 40, e169. https://doi.org/10.1007/s00603-006-0093-8.

Kumar, P., Debele, S.E., Sanahi, J., Rawat, N., Marti-Cardona, B., Alfieri, S.M., Basu, B., Basu, A.S., Bowyer, P., Charizopoulos, N., Jaakko, J., Loupis, M., Menenti, M., Mickovski, S.B., Pfeiffer, J., Pilla, F., Pröll, J., Pulvirenti, B., Rutzinger, M., Sannigrahi, S., Spyrou, C., Tuomenvirta, H., Vojinovic, Z., Zieher, T., 2021. An overview of monitoring methods for assessing the performance of nature-based solutions against natural hazards. Earth. Sci. Rev. 217, e103603. https://doi.org/10.1016/j.earscirev.2021.103603.

Lacambra, C., Möller, I., Spencer, T., 2008. The need for an ecosystem-inclusive vulnerability index for coastal areas in Colombia, in: Bohle, H.-G. (Ed.), Megacities. Resilience and social vulnerability; Outcomes of the 2nd UNU EHS

Summer Academy of the Munich Re Chair on Social Vulnerability, 22–28 July 2007, Hohenkammer, Germany. UNU EHS, Bonn, pp. 82–98.

Lamolda, M.A., Orue-Etxebarria, X., Proto-Decima, F., 1983. The Cretaceous-Tertiary boundary in Sopelana (Biscay, Basque Country). Zitteliana 10, 663–670.

Li, M.H., Eddleman, K.E., 2002. Biotechnical engineering as an alternative to traditional engineering methods: a biotechnical streambank stabilization design approach. Landsc. Urban Plan. 60, 225–242. https://doi.org/10.1016/S0169-2046(02)00057-9.

Li, X., Dong, M., Jiang, D., Li, S., Shang, Y., 2020. The effect of surface roughness on normal restitution coefficient, adhesion force and friction coefficient of the particle-wall collision. Powder Technol. 362, 17–25. https://doi.org/10.1016/j.powtec.2019.11.120.

Marinos, P., Hoek, E., 2001. Estimating the geotechnical properties of heterogeneous rock masses such as flysch. Bull. Eng. Geol. Environ. 60, 85–92. https://doi.org/10.1007/s100640000090.

Martínez, M.L., Psuty, N.P., Lubke, R.A., 2004. A Perspective on Coastal Dunes, in: Martínez, M.L., Psuty, N.P. (Eds.), Coastal Dunes: Ecology and Conservation. Ecological Studies 171, Springer-Verlag, Berlin, pp. 3–10.

McGinnis, R.N., Ferril, D.A., Morris, A.P., Smart, K.J., Lehrmann, D., 2017. Mechanical stratigraphic controls on natural fracture spacing and penetration. J. Struct. Geol. 95, 160–170. https://doi.org/10.1016/j.jsg.2017.01.001.

Miller, R.P., 1965. Engineering classification and index properties for intact rock. PhD Thesis, University of Illinois.

Molina, E., Alegret, L., Apellaniz, E., Bernaola, G., Caballero, F., Dinarès-Turell, J., Hardenbol, J., Heilmann-Clausen, C., Larrasoaña, J.C., Luterbacher, H., Monechi, S., Ortiz, S., Orue-Etxebarria, X., Payros, A., Pujalte, V., Rodríguez-Tovar, F.J., Tori, F., Tosquella, J., Uchman, A., 2011. The Global Stratotype Section and Point (GSSP) for the base of the Lutetian Stage at the Gorrondatxe section, Spain. Episodes 34, 86–108. https://doi.org/10.18814/epiiugs/2011/v34i2/006.

Morales, T., Clemente, J.A., Damás Mollá, L., Izagirre, E., Uriarte, J.A., 2021. Analysis of instabilities in the Basque Coast Geopark coastal cliffs for its environmentally friendly management (Basque-Cantabrian basin, northern Spain). Eng. Geol. 283: e106023 https://doi.org/10.1016/j.enggeo.2021.106023.

Morales, T., Uribe-Etxebarria, G., Uriarte, J.A., Fernández de Valderrama, I., 2004. Geomechanical characterisation of rock masses in Alpine regions: the Basque Arc (Basque-Cantabrian basin, Northern Spain). Eng. Geol. 71, 343–362. https://doi.org/10.1016/S0013-7952(03)00160-1.

Morelli, G.L., 2016. Empirical assessment of the mean block volume of rock masses intersected by four joint sets. Rock Mech. Rock Eng. 49: 1759–1771. https://doi.org/10.1007/s00603-015-0882-z.

Naumann, S., Kaphengst, T., McFarland, K., Stadler, J., 2014. Nature-based approaches for climate change mitigation and adaptation. In: The challenges of climate change – partnering with nature. German Federal Agency for Nature Conservation (BfN). Ecologic Institute, Bonn.

Okura, Y., Kitahara, H., Sammori, T., Kawanami, A., 2000. The effects of rockfall volume on runout distance. Eng. Geol. 58, 109–124.

Palmstrom, A., 2001. Measurement and Characterization of Rock Mass Jointing. in: Sharma, V.M., Saxena, K.R. (Eds.), In-situ characterization of rocks, Chapter 2, A.A. Balkema, London, pp. 1–40.

Palmstrom, A., 2005. Measurement of and correlations between block size and rock quality designation (RQD). Tunn. Undergr. Space Technol. 20, 362–377. https://doi.org/10.1016/j.tust.2005.01.005.

Paronuzzi, P., 2009. Field evidence and kinematical back analysis of block rebounds: the Lavone rockfall, Northern Italy. Rock Mech. Rock Eng. 42, e783. https://doi.org/10.1007/s00603-008-0021-1.

Payros, A., Bernaola, G., Orue-Etxebarria, X., Dinarès-Turell, J., Tosquella, J., Apellaniz, E., 2007. Reassessment of the Early-Middle Eocene biomagnetochronology based on evidence from the Gorrondatxe section (Basque Country, western Pyrenees). Lethaia 40: 183-195. https://doi.org/10.1111/j.1502-3931.2007.00016.x.

Payros, A., Orue-Etxebarria, X., Bernaola, G., Apellaniz, E., Dinarès-Turell, J., Tosquella, J., Caballero, F., 2009. Characterization and astronomically calibrated age of the first occurrence of *Turborotalia frontosa* in the Gorrondatxe section, a prospective Lutetian GSSP: implications for the Eocene time scale. Lethaia 42, 255–264. https://doi.org/10.1111/j.1502-3931.2008.00142.x.

Pfeiffer, T.J., Bowen, T.D., 1989. Computer simulation of rockfalls. Environ. Eng. Geosci. 26: 135–146. https://doi.org/10.2113/gseegeosci.xxvi.1.135.

Pontee, N., Narayan, S., Beck, M.W., Hosking, A.H., 2016. Nature-based solutions: lessons from around the world. Inst. Civ. Eng. Proc. Marit. Eng. 169, 29–36. https://doi.org/10.1680/jmaen.15.00027.

Provoost, S., Jones, M.L.M., Edmondson, S.E., 2009. Changes in landscape and vegetation of coastal dunes in northwest Europe: a review. J. Coast Conserv. 15, 207–226. https://doi.org.10.1007/s11852-009-0068-5.

Ramírez del Pozo, J., 1973. Síntesis geológica de la provincia de Álava. Obra cultural de la Caja de ahorros de la Ciudad de Vitoria, Vitoria-Gasteiz.

Riquelme, A.J., Tomás, R., Cano, M., Pastor, J.L., Abellán, A., 2018. Automatic mapping of discontinuity persistence on rock masses using 3D point clouds. Rock Mech. Rock Eng. 51, 3005–3028. https://doi.org/10.1007/s00603-018-1519-9.

RocPro3D, 2018. RocPro3D software. http://www.rocpro3d.com/rocpro3d_en.php.

RocScience, 2013. Dips, Analyze orientation-based geological data. In: RocScience's User's Guide. https://www.rocscience.com/software/dips.

Rosser, N., Massey, C., 2022. Rockfall hazard and risk, in: Davies, T., Rosser, N., Schroder, J.F. (Eds.), Landslide Hazards, Risks and Disasters, second ed. Elsevier, Amsterdam, pp. 581–622 https://doi.org/10.1016/B978-0-12-818464-6.00013-5.

Sanjaume, E., Gracia, F.J., Flor, G., 2011. Introducción a la geomorfología de sistemas dunares, in: Sanjaume, E., Gracia, F.J. (Eds.), Las dunas en España. Sociedad Española de Geomorfología, Spain, pp. 13–63.

Sarabi, S.E., Han, Q., Romme, A.G.L., De Vries, B., Wendling, L., 2019. Key enablers of and barriers to the uptake and implementation of Nature-Based Solutions in urban settings: a review. Resources 8, e121. https://doi.org/10.3390/resources8030121.

Sarro, R., Riquelme, A., García Lopez-Davalillo, J.C., Mateos, R.M., Tomás, R., Pastor Navarro, J.L., Cano, M., Herrera, G., 2018. Rockfall simulation based on UAV photogrammetry data obtained during an emergency declaration: application at a Cultural Heritage Site. Remote Sens. 10, e1923. https://doi.org/10.3390/rs10121923.

Schmitz, B., Pujalte, V., Molina, E., Monechi, S., Orue-Etxebarria, X., Speijer, R.P., Alegret, L., Apellaniz, E., Arenillas, I., Aubry, M.P., Baceta, J.I., Berggren, W.A., Bernaola, G., Caballero, F., Clemmensen, A., Dinarès-Turell, J., Dupuis, C., Heilmann-Clausen, C., Hilario-Orús, A., Knox, R., Martín-Rubio, M., Ortiz, S., Payros, A., Petrizzo, M.R., Von Salis, K., Sprong, J., Steurbaut, E., Thomsen, E., 2011. The Global Stratotype Sections and Points for the bases of the Selandian (Middle Paleocene) and Thanetian (Upper Paleocene) stages at Zumaia, Spain. Episodes 34, 220–243. https://doi.org/10.18814/epiiugs/2011/v34i4/002.

Sloss, C.R., Hesp, P., Shepherd, M., 2012. Coastal dunes: aeolian transport. Nature Education Knowledge 3, 21.

Solheim, A., Capobianco, V., Oen, A., Kalsnes, B., Wulff-Knutsen, T., Olsen, M., Del Seppia, N., Arauzo, I., García Balaguer, E., Strout, J.M., 2021. Implementing Nature-Based Solutions in rural landscapes: barriers experiences in the PHUSICOS project. Sustainability 13, e1461. https://doi.org/10.3390/su13031461.

Sterr, H., 2008. Assessment of vulnerability and adaptation to sea-level rise for the coastal zone of Germany. J. Coast. Res. 242, 380–393. https://doi.org/10.2112/07A-0011.1.

Tang, J., Zhou, X., Liang, K., Lai, K., Zhou, G., Tan, J., 2021. Experimental study on the coefficient of restitution for the rotational sphere rockfall. Environ. Earth Sci. 80, e419. https://doi.org/10.1007/s12665-021-09684-6.

Touili, N., Baztan, J., Vanderlinden, J.-P., Kane, I.O., Diaz-Simal, P., Pietrantoni, L., 2014. Public perception of engineering-based coastal flooding and erosion risk mitigation options: Lessons from three European coastal settings. Coast. Eng. 87, 205–209. https://doi.org/10.1016/j.coastaleng.2014.01.004.

Tsoar, H., 1983. Wind tunnel modeling of echo and climbing dunes. Dev. Sedimentol. 38, 247–259. https://doi.org/10.1016/S0070-4571(08)70798-2.

Tsoar, H., 2001. Types of Aeolian sand dunes and their formation, in: Balmforth, N.J., Provenzale, A. (Eds), Geomorphological fluid mechanics. Springer-Verlag, Berlin, pp. 403-429. https://doi.org/10.1007/3-540-45670-8_17.

Ulusay, R., 2015. The complete ISRM suggested methods for rock characterization, testing and monitoring: 2007-2014. Springer, Cham. https://doi.org/10.1007/978-3-319-07713-0.

Van der Meulen, F., Ijff, S., Van Zetten, R., 2022. Nature-based solutions for coastal adaptation management, concepts and scope, an overview. Nord. J. Bot., e03290. https://doi.org/10.1111/njb.03290.

Villegas-Palacio, C., Berrouet, L., Marsiglia, S., 2020. Adaptive capacity of households to degradation of Ecosystem Services: a case study in the Colombian Andes. Environ. Manage. 66, 162–179. https://doi.org/10.1007/s00267-020-01305-5.

Vojinovic, Z., Keerakamolchai, W., Torres, A.S., Weesakul, S., Meesuk, V., Alves, A., Babel, M.S., 2021. Towards holistic and multifunctional design of green and blue infrastructure for climate change adaptation in cultural heritage areas, in: Babel, M., Haarstrick, A., Ribbe, L., Shinde, V.R., Dichtl, D. (Eds.), Water Security in Asia - Opportunities and Challenges in the Context of Climate Change. Springer Water Series, Cham, pp. 381-390. https://doi.org/10.1007/978-3-319-54612-4_28.

Volkwein, A., Schellenberg, K., Labiouse, V., Agliardi, F., Berger, F., Bourrier, F., Dorren, L.K.A., Gerber, W., Jaboyedoff, M., 2011. Rockfall characterisation and structural protection – a review. Nat. Hazards Earth Syst. Sci. 11, 2617–2651. https://doi.org/10.5194/nhess-11-2617-2011.

Wang, X.L., Frattini, P., Crosta, G.B., Zhang, L.Q., Agliardi, F., Lari, S., Yang, Z.F., 2014. Uncertainty assessment in quantitative rockfall risk assessment. Landslides 11, 711–722. https://doi.org/10.1007/s10346-013-0447-8.

Wu, B.-S., Ruangpan, L., Sanchez, A., Rasmussen, M., Rene, E.R., Vojinovic, Z., 2021. Environmental design features for large-scale nature-based solutions: Development of a framework that incorporates landscape dynamics into the design of nature-based solutions. Sustainability 13, e6123. https://doi.org/10.3390/su13116123.

4.5. Capítulo V: Rockfall susceptibility analysis through 3D simulations in marine protected areas of the Portofino coastline: case studies of San Fruttuoso and Paraggi bays

Abadía de San Fruttuoso en el Parque Natural de Portofino (Italia)

Jon Ander Clemente, Daniele Spizzichino, Gabriele Leoni, Alessandra Marchese, Jesus A. Uriarte, Tomás Morales, Rolf Wilting, Zoran Vojinovic, Francesco Faccini

Bulletin of Engineering Geology and the Environment

Abstract

The research focuses on the assessment of the potential geomorphological hazards affecting the stability of the Promontory of Portofino (northern Italy), mainly on the bays of San Fruttuoso and Paraggi. The study area constitutes one of the most representative and most populated environments, both by locals and tourists, of the entire Liguria area. For this reason, there is a growing need for investigation on the natural dynamics of these landscapes, based on detailed topographic information. The research starts from a regional geological and geomorphological analysis specific to the study area, combined with a multi-model comparison algorithm (M3C2), which allows comparing two LiDAR datasets acquired in 2008 and 2020, respectively, to assess the overall dynamics of the promontory development. Then, a detailed study of San Fruttuoso and Paraggi bays, two key points for visitors and therefore for management, is performed. Three-dimensional modeling of rockfalls is carried out, which allows the development of a specific management oriented to the use of Nature-Based Solutions (NBSs) strategies, respecting the environment and increasing safety against instability processes in these areas.

Keywords: Geomorphological hazards; Promontory of Portofino; M3C2 algorithm; Three-dimensional rockfall modeling; Nature-Based Solutions (NBSs).

1. Introduction

The paper focuses on the risk assessment of ongoing and potential landslide hazard (e.g. rockfall) affecting the Regional Natural Park of Portofino (Roccati et al. 2021). Located at less than 20km east of Genoa (Liguria region of Italy), the park covers a natural and cultural area of more than 18km^2 whose 13km are of coastal strip. Along the whole area it is possible to walk in a unique natural and cultural heritage, visiting small historical village and sites (e.g. Portofino, Camogli, San Fruttuoso and Paraggi bays) and, at the same time, in a stunning landscape shaped for thousand years (e.g. track trails along the ancient terraces of vineyards and olive grove) (Brandolini et al. 2006; Faccini et al. 2018; Coratza et al. 2019).

Main geo-hazards that affect the site are landslides affected by marine erosion due to sea storms, and both are closely related to the increasing meteo-climatic extreme events, such as windstorms or extreme precipitation, driven by climate changes (Kabisch et al. 2016; Ruangpan et al. 2019; Roccati et al. 2020; Turconi et al. 2020). As a contribution to the short and long-term sustainable conservation policies of sites, a research team was established in the framework of a collaboration among ISPRA, GISIG, Università di Genova and Universidad del País Vasco (UPV/EHU), under the RECONECT Project (www.reconect.eu). In this sense, a specific survey was carried out both in Paraggi and San Fruttuoso bays with the aim to test and calibrate the 3D simulation of rockfalls in the whole Park. The structural setting of the rock mass, related to the stratigraphical setting and to the geomorphological evolution of the slopes, was identified, collected and classified. Additional information on local rock mass conditions, potentially triggering rockfall that may affect both the heritage itself and the visitors, were collected. Some focus areas and catchments were tested in order to assess the preliminary exposure and vulnerability level: the San Fruttuoso Abbey and the Paraggi Bay. Morphometric and geo-mechanical parameters, as input for the modeling, where calibrated along the most representative park trails to check the model's reliability. The activities are characterized thorough multidisciplinary approach (Perrone et al. 2021) including expertise in geomorphology, engineering geology, rock mechanics, nature and earth science, landslide risk assessment and management, as well as conservation, protection and sustainable mitigation measures (Crosta et al. 2017; Calista et al. 2019; Pazzi et al. 2019). Reliable and true advanced modeling results are fundamental for proper conservation and mitigation intervention on the Natural Park heritage. The use of Nature-Based Solutions (NBSs) (Naumann et al. 2014; Kumar et al. 2020; Villegas-Palacio et al. 2020) in areas of high cultural, natural and landscape value is strongly recommended, also because of the high reduction of cost and impact (Debele et al. 2019; Kumar et al. 2021). The above-mentioned collaborative activities, between the different research teams, are aimed at the conservation and protection of cultural landscape site (Jongman 2002), with the ultimate target of making the area accessible to the public in a complete state of safety from rockfalls and slides (Margottini and Spizzichino 2021).

LiDAR technologies developed in this research are now widely used in geological risk management, including rockfall hazard assessment (Kenner et al. 2014; Rieg et al. 2014). LiDAR techniques can provide high resolution and spatially accurate point clouds making them indispensable tools for accurately capturing dense information to facilitate detailed topographic analysis. With this base information, the point clouds modified using cloud processing tools such as CloudCompare, allow the comparison of different LiDAR's with specific algorithms, to determine the regional evolution of the terrain. In this sense, adjusted and georeferenced models can be developed, which combined with three-dimensional simulation software for rockfalls and georeferenced aerial orthophotographies in the same common reference system, let realistic modeling of each studied area.

In our research, we pursue making progress in the recognition of instability processes in the Portofino Park, which preserve a natural environment including San Fruttuoso and Paraggi bays, with the aim of proposing nature-based solution strategies and protection measures above-mentioned in this threatened area. The degree of innovation of this research resides mainly in the combination of studies using in situ and remote techniques for obtaining topographic information, with which to develop three-dimensional modeling to enable specific management for each study area.

2. The Portofino cultural heritage site

Thanks to its wide recognized landscape, natural and cultural values (Fig. 1), the Portofino Promontory has been protected since 1935 with the establishment of the Portofino Natural Park (Coratza et al. 2019). Since 1995, the protected area has been managed by the Regional Park Authority: current protected area is approximately 1,056ha wide, covering the territory of the municipalities of Camogli, Portofino and Santa Margherita Ligure.

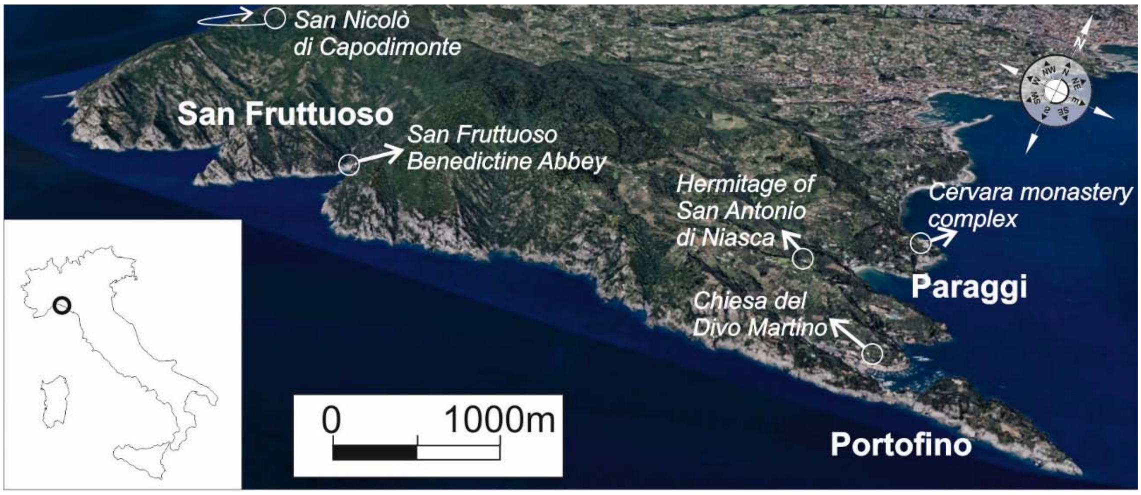


Fig. 1 Geographical context of the study area in Italy and the location of San Fruttuoso, Paraggi and Portofino bays, along with the cultural heritage in Portofino Promontory

The resident population of the Portofino Park is about 750 (Turconi et al. 2020), while the total population of the three municipalities is about 15,000. The number of tourists is very high throughout the year: along the coast, in Portofino town, there are more than one million tourists/year, while in San Fruttuoso the boat connections from the Tigullio and Paradiso Gulfs provide around 400,000 tourists/year (Faccini et al. 2018). In addition to tourists, there are also hikers along the more than 80 km of paths (Brandolini et al. 2006): the section from “Portofino Vetta” to “Pietre strette” is travelled by more than 70,000 hikers/year.

In addition to the Portofino Park, there is the Portofino Marine Protected Area, established in 1999; finally, in 2017 the process to convert Portofino into a National Park was started, even if the boundaries are still to be well defined.

The entire promontory is also extraordinarily rich in cultural heritage, not only represented by the seaside towns of Camogli and Portofino, but above all linked to the ancient medieval religious trails that connected various monastic centers (Figs. 1, 3): on the western side there is the Church of San Nicolò di Capodimonte (Fig. 2a), dating back to the 12th century, in San Fruttuoso there is the Benedictine abbey (Fig. 2b) dating back to the 10th-11th century, on the eastern side there is the Cervara monastery complex (Fig. 2c), built in 1361 and maintained by Benedictine monks. Other important buildings of great cultural interest are the Hermitage of S. Antonio di Niasca, and the Church of Divo Martino in Portofino (Figs. 1, 3).

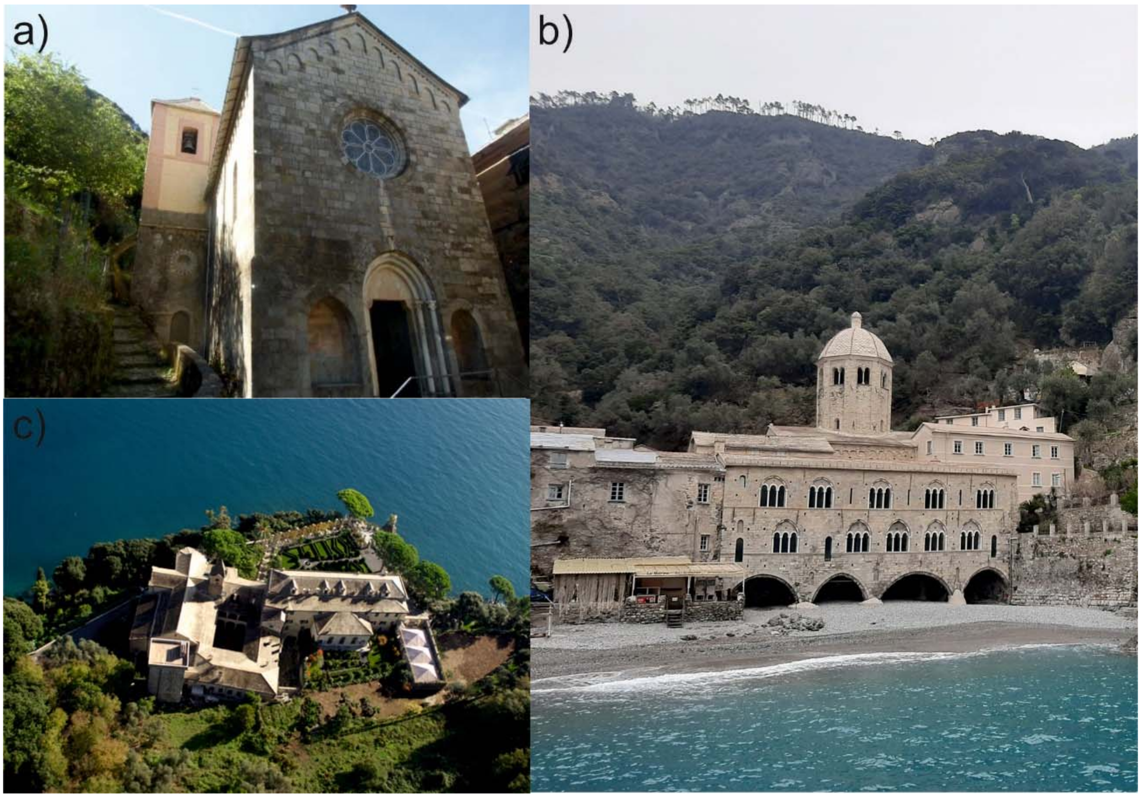


Fig. 2 Some examples of Portofino's cultural heritage: a) Church of San Nicolò di Capodimonte; b) San Fruttuoso Benedictine abbey; c) Cervara monastery complex

Most of this cultural heritage is however threatened by geomorphological hazards: many of these centers were built on ancient and relict landslides (San Nicolò, Divo Martino, S. Antonio di Niasca, Abbazia della Cervara), but occasionally they are reactivated, especially by heavy, short-term rainfall triggered by the atmospheric low depression over the gulf of Genoa (the so-called

“Genoa Low”) (Roccati et al. 2020). On september 25, 1915, an intense and concentrated rainfall triggered a debris-mud flow that channeled into the hydrographic network and partially destroyed the San Fruttuoso abbey and surrounding houses (Paliaga et al. 2022). In fact, it is located exactly at the mouth of the Fontanini valley, which is also subject to frequent rockfall phenomena (Faccini et al. 2008b; 2009). The Cervara complex was severely threatened by the effects of the 2018 Vaia sea storm surge (Biolchi et al. 2019; Turconi et al. 2020; Betti et al. 2021).

3. Geological setting

The geology of the whole area is dominated by two formations (Fig. 3): the “Mt. Antola Flysch” on the north (Elter and Pertusati 1973; Corsi et al. 2001), dated between 90 and 55 million years ago, and the “Portofino Conglomerate” at the south, dated about 30 million years ago (Terranova 1964). Conglomerates, which outcrop at the entire southern slope of the promontory, are made by of heterogeneous pebbles, mainly from marly limestone and secondarily from other lithotypes, in a sandy-limestone matrix (Faccini et al. 2008a). The formation shows a fragile tectonic deformation, with several fault and fracture systems oriented mainly NW-SE and NE-SW (Fig. 3) (Bonaria et al. 2016; Terrone et al. 2021). Regarding the quality indexes of the Portofino Conglomerate, its high resistance stands out (Table 2). At rock mass scale, the Geological Strength Index (GSI) (Marinos and Hoek 2000) ranges from 65 to 70, consequence of the good surface conditions together with a blocky structure (Faccini et al. 2008a). In a detailed scale, field tests using the Schmidt’s Hammer, distinguishing between limestone, arenaceous clasts and matrix (Cevasco et al. 2004), with a modal rate between 25 and 50 were calculated (Faccini et al. 2008a). Besides, laboratory tests have been developed using a Point Load Test, carried out directly on rock samples, and providing compressive strength ranges between 50 and 100 MPa (Faccini et al. 2008a).

Table 2 Rock mass characteristics

MATERIALS	Date	GSI	Schmidt rebound number (modal)	Uniaxial compressive strength (σ_{ci})
Mt. Antola Flysch	55-90M.a.	35-40	15 - 35	30 - 70 MPa
Portofino Conglom.	30M.a.	65 - 70	25 - 50	50 - 100 MPa

This characterization serves as a basis for the definition of different terrains in the modeling part, depending on the values obtained by the techniques used, in addition to the calibration and adjustment process. The tectonic structures, along with the high resistance of the conglomerate, controls the development of instability processes along the entire coastline, which are especially evident in the south-facing conglomeratic outcrops, such as those identified in San Fruttuoso area (Fig. 3).

At present, the bays of San Fruttuoso and Paraggi, respectively located to the south and east of the promontory, have different morphologies. San Fruttuoso has local outcrops of conglomerate, which are found among abundant vegetation of various types, where a deeper terrain is developed, which means that during heavy rainfall, several debris and mudflow processes have historically developed. Shallow landslides often occur in terraced areas with dry stone walls (Paliaga et al. 2016, 2020). In the case of the rocky outcrops, which are relatively isolated and with metric continuity of fractures in the rock mass, rockfalls with spherical shape that exceed one cubic meter are developed. These dimensions of spacing and block volumes are obtained during the days of fieldwork developed in the area, with a classical tape measure, in order to make more accurate measurements for the simulation. On the other side, in Paraggi Bay the coastal zone draws practically a continuous line of rocky cliffs, where diverse processes of rockfalls with decimeters size take place.

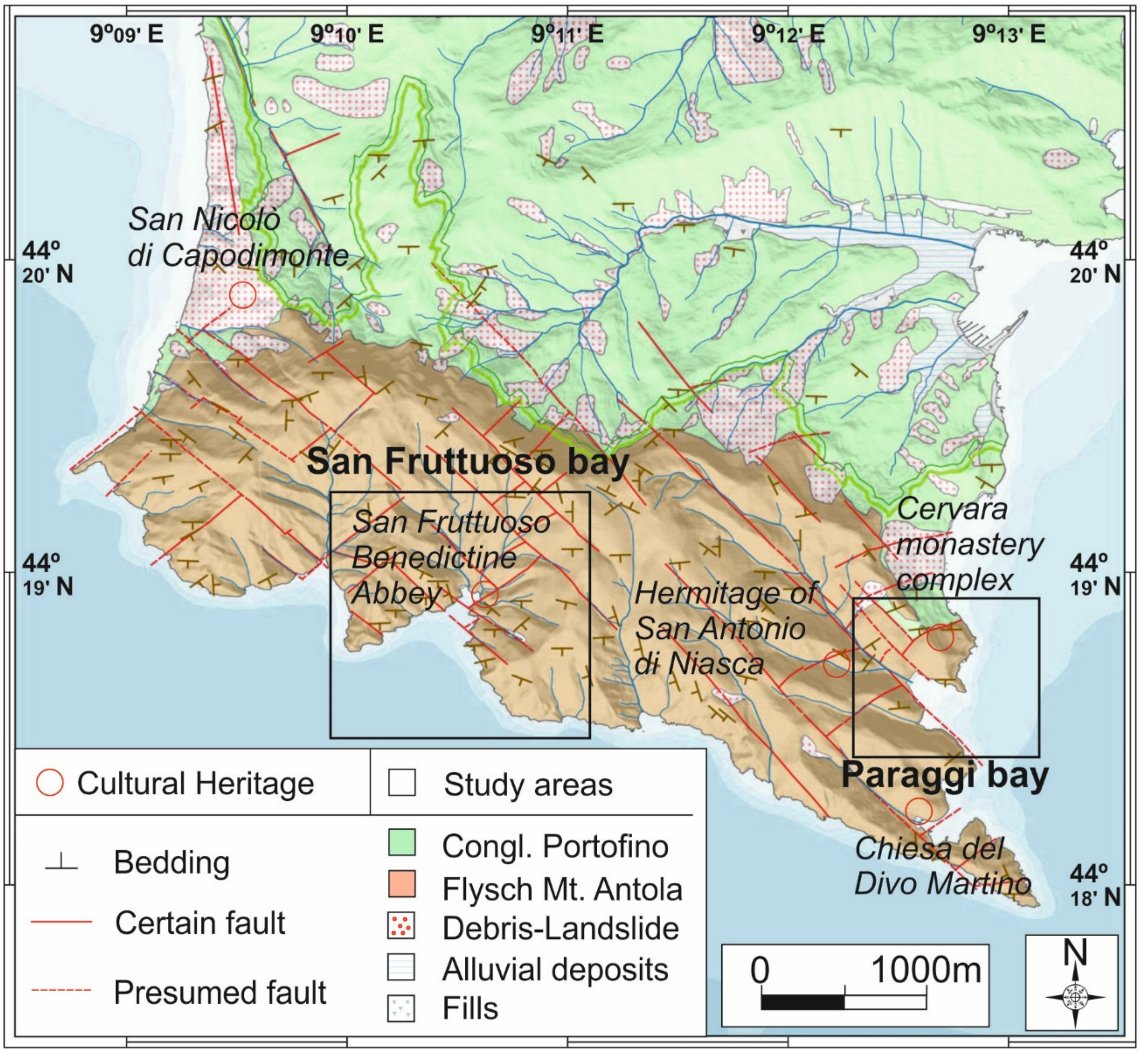


Fig. 3 Geological sketch map of the study area along with the cultural heritage locations (modified from Faccini et al. 2018)

4. Methodology

4.1. Large scale base data and analysis

The study began with the acquisition of the basic topographic information of the ground surface, in order to carry out a general morphometric and geomorphological analysis at the scale of the Promontory of Portofino. This preliminary study was conducted to perform then detailed analyses of the areas of greatest activity and interest, in those that demonstrate modifications on a general scale, and where numerous events have been identified over the last few years.

In the regional context, a comparison was made between the LIDARs 2008 (by the Italian Ministry of the Environment) and 2020 (acquired by EUROSENSE in the framework of RECONECT project), after the necessary Coordinate Reference System alignment using the Open Access GIS QGIS (v. 3.14). This preliminary work was made based on the multiscale model-to-model cloud comparison (M3C2) algorithm through CloudCompare software (James et al. 2017; DiFrancesco et al. 2020; Bernard et al. 2021; Hu et al., 2022).

4.2. Detailed topographic information

Once the general framework was completed, based on this information, a local study of San Fruttuoso and Paraggi bays, south sector of the Promontory, was carried out. Using the free CloudCompare v.2.12 Alpha software, the original LiDAR was modified and the specific DTM of each zone was elaborated, for analysis in raster format, by projecting the point cloud perpendicularly onto a flat raster surface, with a cell size of 0.5 m. The raster was then combined with georeferenced orthophotos, which is combined with above-mentioned information through Geographic Information System QGIS 3.6 NOOSA.

From the detailed DTMs, the basic point cloud was extracted and, by means of a triangulation process using the Delaunay method performed in RocPro3D software (RocPro3D 2018), a three-dimensional mesh reflecting the real relief of the environment was obtained. All the data regarding terrain properties and instability processes were added to the model, and were represented over the orthophoto, allowing working with detailed realistic three-dimensional model of the study area.

4.3. Modeling and simulation of rockfalls

The development on the ground of rockfalls is limited by the dispersion of their energy, which is usually approximated by two coefficients (Pfeiffer and Bowen 1989; Morales et al. 2021): the normal coefficient of restitution (Rn), which indicates the degree of elasticity in a normal collision with the slope; and the tangential coefficient of restitution (Rt), which is a measure of the resistance to movement parallel to the slope (Pfeiffer and Bowen 1989), which are calculated by the following expressions (Li et al. 2020; Wang et al. 2020; Morales et al. 2021; Zhang et al. 2021):

Reflected normal velocity ($v_{n,r}$):

$$v_{n,r=} = \frac{v_{n,i} \cdot Rn}{1+\left(\frac{|v_{n,i}|}{K}\right)^2} \qquad (1)$$

Where:

$v_{n,i}$= incident normal velocity,

K=empirical reference velocity

Reflected tangential velocity($v_{t,r}$)

$$v_{t,r} = \sqrt{\frac{R^2 \cdot \left(I \cdot \omega_{(1)}{}^2 + m \cdot v_{t,i}{}^2\right) \cdot FF \cdot SF}{I + m \cdot R^2}} \qquad (2)$$

Where:

R = radius of the rock

$\omega_{(1)}$= initial rotational velocity

m= rock mass

$v_{t,i}$= initial tangential velocity

FF= friction function

SF =scaling factor

I = rock moment of inertia.

By means of these two equations, the restitution coefficients that will be fundamental in the rockfall modeling process and which are characteristic of each differentiated terrain are acquired, in addition to other factors such as dynamic friction (k) and vertical and lateral deviation acquired from contrasted previous researches.

4.4. Three-dimensional rockfall modeling

The modeling process was approached by using RocPro3D software (RocPro3D, 2018). This software performs three-dimensional simulations of individual trajectories from a Digital Terrain Model (DTM), which is extracted from the above-mentioned acquired topography. Software permits generating a mesh developed by triangulation as stated before. The mesh is the beginning of the model, which represent the real relief of the studied environment, on which the simulation of rockfall from the identified source areas is carried out. This type of modeling allows including the lateral evolution of rockfalls.

For the definition of the source areas, it is essential to carry out fieldwork to identify and locate exactly the origin of the rockfalls, evaluating scars in the rock mass (Palmstrom 2005; Corominas et al. 2017), which will then be reflected in the models. Regarding the volume established, the study has been prioritized for rocks of $1m^3$, which is the largest size recorded in the area and also the highest energy (Corominas et al. 2017; Morales et al. 2021), except for the specific case studied below, where a block reached $3m^3$.

In order to calibrate the input parameters of the modeling, the first step has been to carry out a recent papers review of several authors working in different terrains (Ji et al. 2020; Ji et al. 2021; Tang et al. 2021; Ye et al. 2021; Prades-Valls et al. 2022; Sardana et al. 2022; Shadabfar et al. 2022), with the aim of frame each of those defined in San Fruttuoso and Paraggi within established limits. From this starting point, rebound values were calibrated via 3D back analysis to achieve the best agreement between observations and modeling estimates (Sarro et al., 2018; Fanos and Pradhan, 2019)

Finally, it should be noted that in the modeling the densely vegetated areas have also been characterized and established, since they represent a degree of protection that less abundant vegetation does not provide. Likewise, in this case, land uses as such have not been taken into account, since this section is contemplated in the proposed solutions of the mitigation plan. However, anthropic materials are defined, such as roads and walkways, with resistance values different from other identified materials, since they condition the rebound and evolution of the blocks in a completely different way.

5. Results

5.1. Large scale DTM comparison through M3C2 algorithm

The DTM assessment, obtained via the CloudCompare (v. 2.12 Alpha) software, has been established using the multiscale model-to-model comparison (M3C2) algorithm, which is a robust way to compute distances directly between two point clouds, established with limits of -1 to 1 meter, since, being 12 years apart, it is estimated that the vast majority of ground movements are local and with a decimeter difference (Fig. 4).

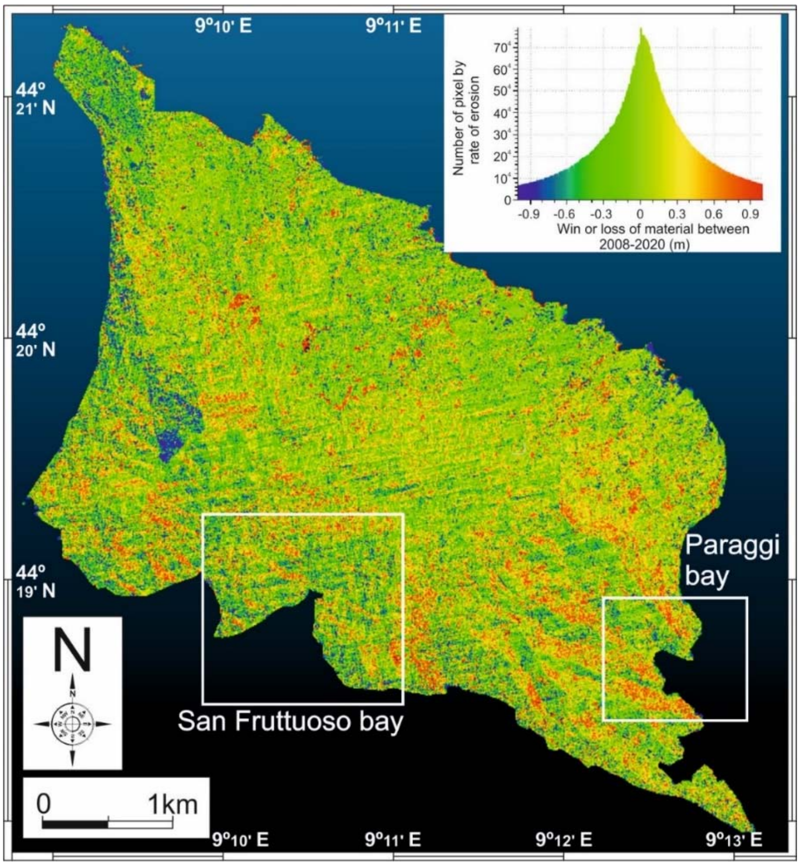


Fig. 4 Comparison between the elevations of the 2008 and 2020 DTMs on the Portofino's Promontory

This comparison makes it possible to identify that the study area is relatively stable from the viewpoint of slope stability and erosion, since differences close to zero (green color) predominate throughout the sector. However, significant differences can be identified between the northern area, with less evolution, and the southern area, where significant settlements of around 1 meter (blue color) and raise of up to 1 meter (red color) can be identified. Often, especially remarkable in San Fruttuoso, these zones of gain or losses of terrain elevation are aligned to NW-SE orientation (structural patterns that control hydrographic network evolution), that fits with the ground movements highlighted by the Geological Survey of Italy (ISPRA) in the "Dissesto idrogeologico in Italia: pericolosità e indicatori di rischio – Edizione 2018", where the landslide hazard of the area under study was collected (Fig. 5).

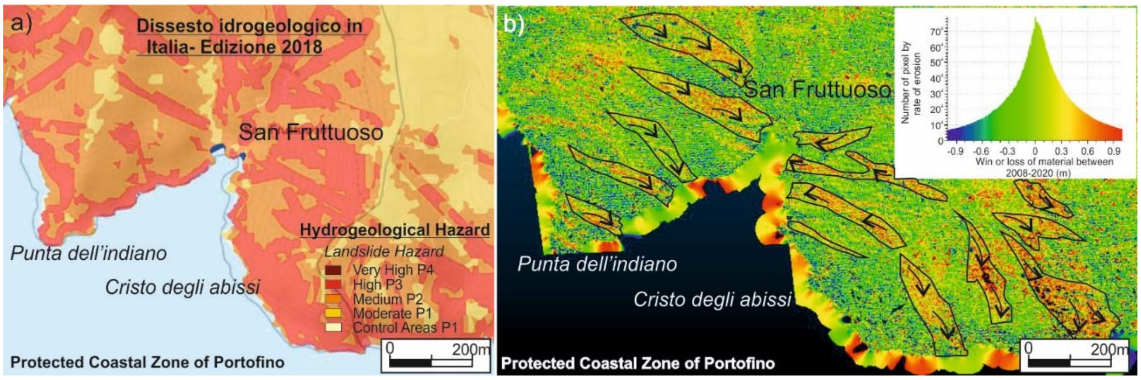


Fig. 5 Comparison between: a) the landslide hazard analysis map developed by the Geological Survey of Italy (ISPRA) and b) our comparison between DTM's

5.2. 3D modeling terrains adjusted parameters

In order to perform a detailed analysis of the rockfall processes in San Fruttuoso and Paraggi bays, specific models of both areas have been generated from the topographic information described above.

For an accurate representation of the rockfalls occurring in the study area, the terrains must be differentiated and defined in the field (Pfeiffer and Bowen 1989), as well as their values of dynamic friction (k), normal and tangential restitution coefficients (R_n and R_t, respectively) and final degree of lateral and vertical deviation (Guzzetti et al. 2003), which absolutely affect the development of the rock fragments. Calibration accuracies were calculated based on comparison of inventory and simulated raster pixels, and were found to be 95% (Fanos and Pradhan 2019), along with the subsequent adjustment as defined in the methodological section, ending with the values for each differentiated terrain shown in Table 1.

Table 1 Terrain properties and adjusted parameters in San Fruttuoso and Paraggi bays

MATERIAL PROPERTIES		**Porto. Conglomerate**	**Loose soil with vegetation**	**Access area**	**Water surface**
Restitution coefficients (R)	*units*				
Mean normal value μ_Rn		0.55	0.3	0.5	0
Mean tangential value μ_Rt		0.9	0.8	0.8	0
Std.-Dev. σ_R		0.011	0.012	0.016	0
Limit velocity V_R (lim)	(*m/s*)	10	10	10	0
Limit Std.-Dev. σ_R (lim)		0.0055	0.006	0.012	0
Lateral deviation (θh)					
Std.-Dev. σ_θh	(º)	10	5	7.5	0
Limit velocity V_θh	(*m/s*)	10	10	10	0
Limit Std.-Dev. σ_θh (lim)	(º)	5	2.5	3.75	0
Vertical deviation (θv)					
Std.-Dev. σ_θv	(º)	1	1	1	0
Limit velocity V_θv	(*m/s*)	10	10	10	0
Limit Std.-Dev. σ_θv (lim)	(º)	2	2	2	0
Friction coefficient (k)					
Mean value μ_k		0.45	0.6	0.5	0
Std.-Dev. σ_k		0.036	0.045	0.045	0
Limit velocity V_k (lim)	(*m/s*)	10	10	10	0
Limit Std.-Dev. σ_k (lim)		0.03	0.03	0.03	0

5.3. 3D local simulation of rockfalls: San Fruttuoso and Paraggi bays

With this baseline information, 14 rockfall source areas have been identified in San Fruttuoso and 8 in Paraggi fieldworks, from which 350 and 120 trajectories have been simulated, respectively. Despite there are areas with relatively smaller blocks, a diameter of 1m has been standardized for spherical blocks (Fanos and Pradhan 2019) detached from conglomeratic outcrops, as the highest energy identified for the pilots. As for the size of the blocks, a necessary input to develop a model (Hungr et al. 1999), only one exception has been made, and that is the source area identified in the 25th October 2016 rockfall in San Fruttuoso, where a detached block of 3m diameter, much larger than the one currently identified in the bay, destroyed a house (Fig 7f).

Due to the geomorphology of the San Fruttuoso Bay, and mainly on its northwest flank, rockfall trajectories tend to concentrate in small canyons, identifiable with the field survey, which are in turn the preferential waterways. The southeastern flank, however, due to the proximity and the verticality of the conglomeratic cliffs to the sea, develops almost straight trajectories (Fig. 6a). Paraggi Bay, on the other hand, depicts a much more direct rockfall dynamic, with vertical cliffs close to the main road and the sea, which address this evolution (Fig. 6b).

5.4. 3D trajectories, energy and runout analysis

Given that the Paraggi sector has undergone numerous instability processes in recent years, it is an area where the managing authorities have carried out numerous constructive actions, making it a relatively less natural area and therefore less suitable for the study presented. Thus, a more in-depth analysis was proposed in the San Fruttuoso area, where instability processes are taking place, but on largely natural spaces that have not yet been acted upon, which facilitates the proposal of actions based on the NBSs.

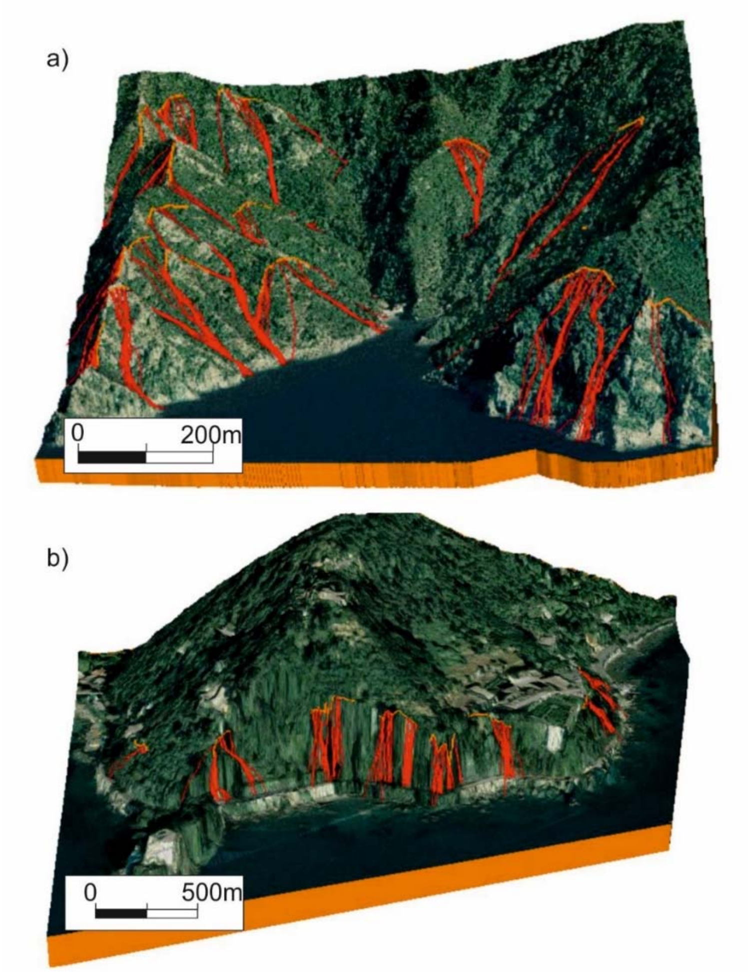


Fig. 6 3D model showing scarp main active source areas (orange lines) and trajectories (red lines) of a) San Fruttuoso Bay and b) high rocky coast on the eastern side Paraggi Bay

Two trajectories have been selected in San Fruttuoso Bay, representing a higher degree of exposure and hazard for both the structures, tourist and residents in the area. On the one hand, there is an area of special interest and need for protection, which is represented by trajectory 198 (Fig. 7a), on the northwest flank, whose path ends in the restaurant at the foot of the slope (Fig. 7e). On the other hand, trajectory 304 (Fig. 7c) represents the most important recent episode that has occurred in the bay in 2016 (back analysis approach), where a block 3m wide hit a house and destroyed it (Fig. 7f). The large amount of data collected in this episode allow for a more calibrated and robust model. An individual analysis of these trajectories has been modeled, analyzing the energy during their entire trajectory (He et al. 2020), the rebound zones and the stopping zone (Fig. 7b, d).

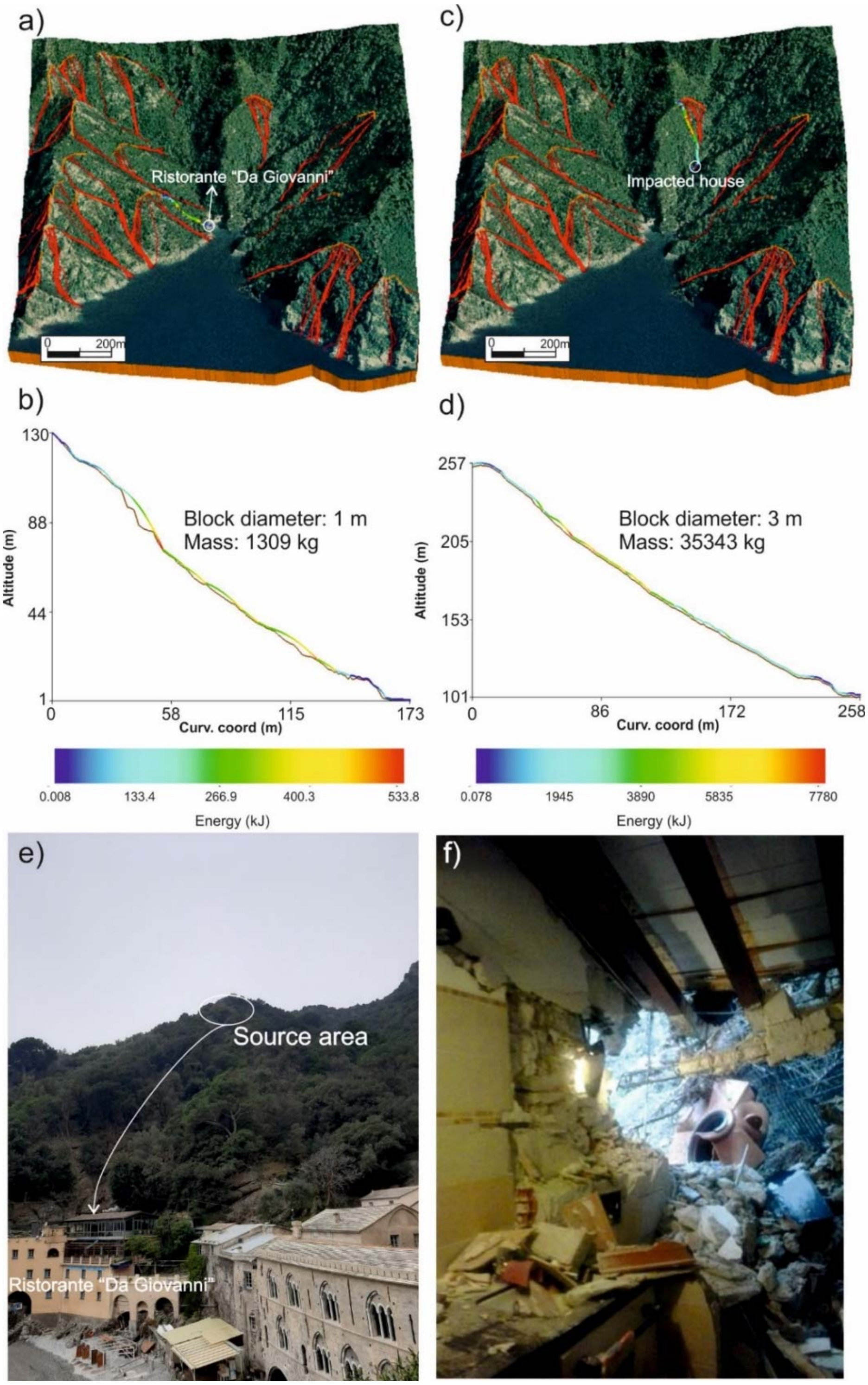


Fig. 7 Analysis of individual trajectories of rockfalls: a) trajectory 198 in the 3D simulation; b) energy profile of trajectory 198; c) trajectory 304 in the 3D simulation; d) energy profile of trajectory 304; e) potential rockfall trajectory 304 and f) house destroyed by rockfall in 2016

5.5. Elaboration of maps and valuation of results

In addition to the simulation of individual trajectories, three-dimensional modeling allows the production of maps of different parameters that can address the management of these spaces (Sarro et al. 2018; Fanos and Pradhan 2019; Akin et al., 2021). For the elaboration of these analysis maps, the terrain is divided into cells of 5x5 meters, which in the case of San Fruttuoso were 308 horizontal and 377 vertical cells, giving almost 120,000 simulation cells. In this way, the fundamental parameters are calculated for each cell resulting from the rockfall modeling (Akin et al. 2021; Clemente et al. 2021). In the case of the present study, all analysis maps are performed for a Confidence Limit (CL) of 95%, such as: a) energy, representing the maximum energy recorded; b) height, the maximum vertical height of the trajectories; c) density, number of rocks passing through each cell; d) impacts, the number of impacts by cell; e) velocity, maximum speed reached by the falls; and f) minimum time, the time interval between the rock detachment and its stop (Fig. 8).

As for the energy map, the maximum energy reached is, in specific and scattered cases, 1,600 kJ, although practically all the detachments collected in the cells comprise energies of a few hundred at the origin, 800-1,200 in the impact zones, which usually evolve towards 1,400 kJ (Fig. 8a). Regarding the vertical height of the rockfalls, which are fundamental input parameter for sizing the mitigation measures (e.g. barriers, meshes, walls) needed to stop the most dangerous blocks, rarely it is greater than 5 m, except in specific cases where the coastal strip is more verticalized, which are mainly located far from the accessible areas (Fig. 8b). The number of trajectories per cell (Fig. 8c) and the impacts (Fig. 8d) are mainly concentrated on the levels previously recognized in the individual trajectories. With respect to the speed of the falls calculated in the maps, three phases are evidenced: the first 5-10 meters of the trajectories, with speeds of less than 5m/s; an intermediate and longest zone, between 60-90 meters, with speeds around 16m/s where the blocks accelerate; and final part, 10-30 meters long, where speeds of more than 30m/s are reached (Fig 8e), exhibiting maximum fall times of 70 seconds, although times around 30 are more common (Fig. 8f).

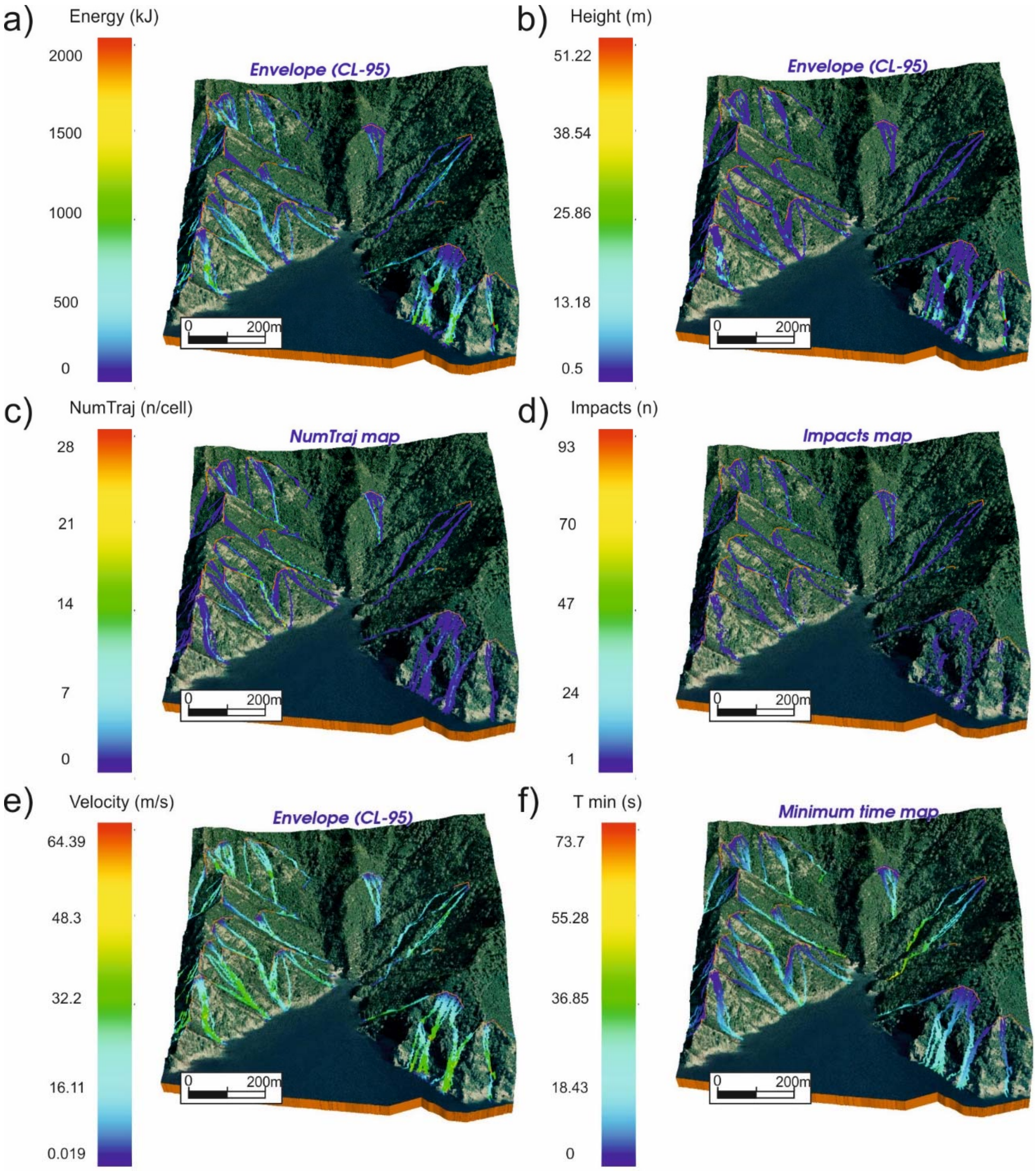


Fig. 8 Cell-based analysis maps of simulated rockfall parameters for a Confidence Limit (CL) of 95% in the San Fruttuoso Bay: a) energy; b) height; c) number of trajectories; d) impacts; e) velocity and f) minimum path time

6. Proposal for a short- and long-term low impact (NBSs) mitigation master plan

In the whole investigated area, the present and active morphological processes should be framed within a management and conservation master plan having two different timeline references: emergency mitigation measures, to be defined and undertaken in the short-medium-term, and preventive mitigation measures to be implemented in the medium-long term (Spizzichino et al. 2016).

Short-medium term actions should be always preceded by an investigation phase including:

- Field survey and detailed geomatics Terrestrial Laser Scanner (TLS) acquisition coupled with UAV flight acquisition, in order to provide high-resolution 3D topographical models of the whole heritage area.
- Laboratory and in situ test execution.
- Detailed geomorphological and geo-mechanical survey of the rock slope.
- Global kinematic analysis of the rock including the calculation of the most probable rockfall trajectories (3D rockfall modeling).
- Exposure and vulnerability assessment and mapping of the natural and cultural heritage in the area.
- Detailed landslide hazard and risk assessment.
- Slope stability modeling (2D and 3D) for specific blocks and/or unstable portions of the cliff.
- Temporary supports of unstable rock portions.
- Urgent reinforcement in the most instable volumes to avoid detachments.

- Redefinition of touristic paths and accesses, to prevent tourists from being exposed to potential collapses or instabilities.

- New communication plan and billboard for touristic management.

The long-term actions include:

- General master plan with detailed design of mitigation through NBSs approach.

- Design of an integrated monitoring system. The adopted monitoring integrated system could also be set, with some small modifications and thresholds definition, as a warning system for flash flood as well as for detection of large rock block deformations.

In both cases, the mitigation options must be supported by scientific and technical analysis in a holistic framework. The proposed numerical 3D rockfall modelling is a fundamental tool to support the above-mentioned strategies.

7. Discussion

The management of coastal areas needs to advance in methodological approaches that allow detailed studies of the current dynamics, in order to develop specific management plans for each environment, based on the guidelines of the NBSs (Villegas-Palacio et al. 2020; Kumar et al. 2021; Vojinovic et al. 2021). In previous works, a large number of authors have assessed these strategies as a line of action for natural hazards in different environments (Pontee et al. 2016; Castelle et al. 2019; Van der Meulen, 2022), but rarely dedicated to geological hazards.

The proposed study in the Portofino Natural Park has allowed the development of a methodology that combines remote sensing techniques with local digital terrain models, as long as with data collection through fieldwork. This detailed topographic information is derived to the design of three-dimensional point clouds, which are modified and adjusted by means of specific software, which serve as a basis for the elaboration of investigations on slopes that present complex morphology (Abellán et al. 2010; Pham et al. 2016; Ansari et al. 2018), such as the coastline of Portofino, and especially the San Fruttuoso Bay, where a realistic representation of the relief is the only way to develop geo-hazard studies useful in future management strategies (Ratter, 2013; Jia et al., 2016; Preti et al., 2021).

The advance of adding a third dimension to traditional 2D rockfall modeling involves taking into account the lateral deviation of block trajectories (Bourrier et al. 2012; Asteriou and Tsiambaos 2018; Ji et al. 2020), which was previously overlooked considering only terrain profiles, and which is essential to understand the processes in detail in order to mitigate their negative impacts (Volkwein et al. 2011). This is especially important in coastal environments, where sometimes the shape of the cliffs tends to develop trajectories with lateral evolutions almost in their entirety.

The detailed analysis of the most important rockfall trajectories studied in the past (most of them of $1m^3$), that reach high energies and volumes up to $3m^3$, even destroying local structures, lead to study and recognize the potential new events in the selected environments, with which evaluate, adjust and simulate detachments occurring in the near and far future. Thus, it will be possible to develop management strategies that adhere to the environment in a more respectful, environmentally friendly, controlled and efficient way, improving in turn the safety against geo-hazards (Morales et al. 2021; Domínguez-Cuesta et al. 2022). These actions that combine constructive elements with warning campaigns and delimitation of access and use areas, will result in establishing a base methodology applicable to other environments with similar characteristics, where the population's negative perception because of these interventions will be significantly reduced (Touili et al. 2014; Gray et al. 2017).

The development of analysis maps of different parameters that define rockfalls makes it possible to analyze the necessary height and the minimum energy that the hypothetical control structures to be installed in the area should withstand, or the response time and velocity against possible block falls (Sarro et al. 2018; Fanos and Pradhan 2019; Akin et al., 2021). This information provides a deeper understanding of the dynamics of instability processes in the environment, which in any case must constantly update its data and add new information, in order to progressively generate more realistic and accurate models of the environment.

8. Conclusions

The investigated area of Portofino Natural Park, covers a wide natural and cultural area where it is possible to visit remarkable heritage sites walking in an incredible high value landscape. The entire area is characterized by the presence of conglomerate rocks. The geological and geo-mechanical characteristics of this formation affect the potential instability of the natural and cultural heritages sites, especially during heavy rainfall and extreme events.

In the present paper a comprehensive analysis of potential instability mechanisms (rockfall) and their spatial evolution (e.g. runout distance, trajectories and impact energy) is described for the selected area of San Fruttuoso and Paraggi bays. Such approach and methodology allow to carry out further studies and analysis supporting the adoption of the so-called Nature-Based Solutions (NBSs), aiming to reduce the impact by the construction of mitigation measures and to increase resilience in high value natural and cultural area.

At the same time, the proposed advanced modeling constitutes a useful tool for the verification and calibration of the adopted design choices (e.g. size and correct location of the barriers, hypothesis of structural interventions for the protection of exposed elements such as paths, terraces and cultural heritage), as well as a useful guidance for the implementation of medium/long-term non-structural measures, such as in situ monitoring systems to be eventually transformed into early warning systems.

The detailed knowledge of the morphological dynamics of the area are in fact a fundamental cognitive element to develop participatory planning, directly involving stakeholders and providing the tools for a correct cost-benefit analysis to policy makers and funders. A co-creation process, in fact, runs across all the steps for the implementation of NBSs interventions, from the initial co-design, to co-monitoring of their performance, to maintenance and finally decommissioning.

The advanced 3D modeling phase here proposed, in addition to being a real digital twin of the natural dynamics of the area, is expected to be integrated into this co-creation process for the sustainable management of high value areas.

Acknowledgement

This study has been carried out in the framework of a collaboration among ISPRA, GISIG, Università di Genova and Universidad del País Vasco (UPV/EHU) within the RECONECT Project (Regenerating ECOsystems with Nature-based solutions for hydro-meteorological risk rEduCTion). RECONECT project received funding from the European Union's Horizon 2020 Research and Innovation Program under grant agreement No 776866.

References

Abellán A, Calvet J, Vilaplana JM, Blanchard J (2010) Detection and spatial prediction of rockfalls by means of terrestrial laser scanner monitoring. Geomorphology 119: 162-171. https://doi.org/10.1016/j.geomorph.2010.03.016

Akin M, Dinçer I, Ok AO, Orhan A, Akin MK, Topal T (2021) Assessment of the effectiveness of a rockfall ditch through 3-D probabilistic rockfall simulations and automated image processing. Eng Geol 283: 106001. https://doi.org/10.1016/j.enggeo.2021.106001

Ansari MK, Ahmad M, Singh R, Sing TN (2018) 2D and 3D rockfall hazard analysis and protection measures for Saptashrungi Gad Temple, Vani, Nashik, Maharashtra – A case study. J Geol Soc India 91: 47-56. https://doi.org/10.1007/s12594-018-0819-8

Asteriou P, Tsiambaos G (2018) Effect of impact velocity, block mass and hardness on the coefficients of restitution for rockfall analysis. Int J Rock Mech Min Sci 106: 41–50. https://doi.org/10.1016/j.ijrmms.2018.04.001

Bernard TG, Lague D, Steer P (2021) Beyond 2D landslide inventories and their rollover: synoptic 3D inventories and volume from repeat lidar data. Earth Surf Dynam 9: 1013-1044. https://doi.org/10.5194/esurf-9-1013-2021

Betti F, Venturini S, Merotto L, Cappanera V, Ferrando S, Aicardi S, Mandich A, Castellano M, Povero P (2021) Population trends of the fan mussel Pinna nobilis from Portofino MPA (Ligurian Sea, Western Mediterranean Sea) before and after a mass mortality event and a catastrophic storm. Eur Zool J 88 (1): 18-25. https://doi.org/10.1080/24750263.2020.1850891

Bonaria V, Faccini F, Galiano IC, Sacchini A (2016) Hydrogeology of conglomerate fractured-rock aquifers: An example from the Portofino's Promontory (Italy). Rendiconti Online Soc Geol Ital 41: 22-25. https://doi.org/10.3301/ROL.2016.83

Bourrier F, Berger F, Tardig P, Dorren L, Hungr O (2012) Rockfall rebound: comparison of detailed field experiments and alternative modelling approaches. Earth Surf Process Landf 37: 656–665. https://doi.org/10.1002/esp.3202

Brandolini P, Faccini F, Piccazzo M (2006) Geomorphological hazard and tourist vulnerability along Portofino Park trails (Italy). Nat Hazards Earth Syst Sci 6: 563-571. https://doi.org/10.5194/nhess-6-563-2006

Calista M, Miccadei E, Piacentini T, Sciarra N (2019) Morphostructural, meteorological and seismic factors controlling landslides in weak rocks: the case studies of Castelnuovo and Ponzano (North East Abruzzo, Central Italy). Geosciences 9(3):122. https://doi.org/10.3390/geosciences9030122

Castelle B, Laporte-Fauret Q, Marieu V, Michalet R, Rosebery D, Bujan S, Luban B, Bernard JP, Valance A, Dupont P, Oul El Moctar A, Narteau C (2019) Nature-based solution along high-energy eroding sandy coasts: Preliminary tests on the resinstatement of natural dynamics in reprofiled coastal dunes. Water 11: e2518. https://doi.org/10.3390/w11122518

Cevasco A, Faccini F, Nosengo S, Olivari F, Robbiano A (2004) Valutazioni sull'uso delle classificazioni geomeccaniche nell'analisi della stabilit`a dei versanti rocciosi: il caso del Promontorio di Portofino (Provincia di Genova), GEAM 11: 31–38.

Clemente JA, Uriarte JA, Apraiz A, Morales T (2021). Modelización de caída de rocas en los acantilados carbonatados "tipo flysch" de la playa de Atxabiribil (Sopela, Bizkaia): análisis tridimensional. Rev Soc Geol Esp 34 (2): 52-63.

Coratza P, Vandelli V, Fiorentini L, Paliaga G, Faccini F (2019) Bridging Terrestrial and Marine Geoheritage: Assessing Geosites in Portofino Natural Park (Italy), Water 11, 2112. https://doi.org/10.3390/w11102112

Corominas J, Mavrouli O, Ruiz-Carulla R (2017) Rockfall ocurrence and fragmentation, in: Sassa, K., Mikoš, M., Yin, Y. (Eds), Advancing culture of living with landslides. Springer, Cham, pp 75–97 https://doi.org/10.1007/978-3-319-59469-9_4

Corsi B, Elter FM, Giammarino S (2001) Structural fabric of the Antola Unit (Riviera di Levante, Italy) and implications for its Alpine versus Apennine origin. Ofioliti 26: 1-8.

Crosta GB, Agliardi F, Rivolta C, Alberti S, Dei Cas L (2017) Long-term evolution and early warning strategies for complex rockslides by real-time monitoring. Landslides 4(5):1615–1632. https://doi.org/10.1007/s10346-017-0817-8

Debele SE, Kumar P, Sahani J, Marti-Cardona B, Mickovski SB, Leo LS, Porcù F, Bertini F, Montesi D, Vojinovic Z, Di Sabatino S (2019) Nature-based solutions for hydro-meteorological hazards: Revised concepts, classification schemes and databases. Environ Res 179: 1-20. https://doi.org/10.1016/j.envres.2019.108799

DiFrancesco PM, Bonneau D, Hutchinson J (2020) The Implications of M3C2 Projection Diameter on 3D Semi-Automated Rockfall Extraction from Sequential Terrestrial Laser Scanning Point Clouds. Remote Sens 12(11): 1885. https://doi.org/10.3390/rs12111885

Domínguez-Cuesta MJ, González-Pumariega P, Valenzuela P, López-Fernández C, Roríguez-Rodríguez L, Ballesteros D, Mora M, Meléndez M, Herrera F, Marigil MA, Pando L, Cuervas-Mons J, Jiménez-Sánchez M (2022). Understanding the retreat of the Jurassic Cantabrian Coast (N. Spain): Comprehensive monitoring and 4D evolution model of the Tazones Lighthouse landslide. Mar Geol 449: 106836. https://doi.org/10.1016/j.margeo.2022.106836

Elter P, Pertusati PC (1973) Considerazioni sul limite Alpi-Appennino e sulle relazioni con l'arco delle Alpi occidentali. Mem Soc Geol It 12: 359-375.

Faccini F, Piccazzo M, Robbiano A, Roccati A (2008a) Applied geomorphological map of the Portofino Municipal Territory (Italy). J Maps 4(1): 451-462. https://doi.org/10.4113/jom.2008.1023

Faccini F, Piccazzo M, Robbiano A (2008b) Environmental Geological Maps of San Fruttuoso Bay (Portofino Park, Italy). J Maps 4(1): 431-443. https://doi.org/10.4113/jom.2008.1018

Faccini F, Piccazzo M, Robbiano A (2009) Natural hazards in San Fruttuoso of Camogli (Portofino Park, Italy): a case study of a debris flow in a coastal environment. Bollettino della Società Geologica Italiana (It. Jour. Geol.) 128: 641-654.

Faccini F, Paliaga G, Piana P, Gabellani N, Angelini S, Coratza P (2018) The Geoheritage map of the Portofino Natural Park (Italy) as a tool for the management of a highly frequented protected area. J Maps 14(2): 87-96. https://doi.org/10.1080/17445647.2018.1433561

Fanos AM, Pradhan B (2019) A novel rockfall hazard assessment using laser scanning data and 3D modelling in GIS. Catena 172: 435–450. https://doi.org/10.1016/j.catena.2018.09.012

Geological Survey of Italy (ISPRA) (2018) Dissesto idrogeologico in Italia: pericolosità e indicatori di rischio.

Gray JDE, O'Neill K, Qiu Z (2017) Coastal residents' perceptions of the function of and relationship between engineered and natural infrastructure for coastal hazard mitigation. Ocean Coast Manag 146: 144–156. https://doi.org/10.1016/j.ocecoaman.2017.07.005

Guzzetti F, Reichenbach P, Wieczorek GF (2003) Rockfall hazard and risk assessment in the Yosemite Valley, California, USA. Nat. Hazards Earth Syst Sci 3: 491–503. https://doi.org/10.5194/nhess-3-491-2003

He K, Li Y, Ma G, Hu X, Liu B, Ma Z, Xu Z (2020) Failure mode analysis of post-seismic rockfall in shattered mountains exemplified. Landslides 18: 425-446. https://doi.org/10.1007/s10346-020-01532-1

Hu L, Navarro-Hernández MI, Liu X, Tomás R, Tang X, Bru G, Ezquerro P, Zhang Q (2022) Analysis of regional large-gradient land subsidence in the Alto Guadalentín Basin (Spain) using open-access aerial LiDAR datasets. Remote Sens Environ 280: 113218. https://doi.org/10.1016/j.rse.2022.113218

Hungr O, Evans SG, Hazzard J (1999) Magnitude and frequency of rock falls and rock slides along the main transportation corridors of southwestern British Columbia. Can Geotech J 36: 224–238. https://doi.org/10.1139/t98-106

James MR, Robson S, Smith MW (2017) 3-D uncertainty-based topographic change detection with structure-from-motion photogrammetry: precision maps for ground control and directly georeferenced surveys. Earth Surf Process Landf 42(12): 1769-1788. https://doi.org/10.1002/esp.4125

Ji ZM, Chen ZJ, Niu QH, Wang TH, Wang TJ, Chen TL (2020) A calculation model of the normal coefficient of restitution based on multi-factor interaction experiments. Landslides 18: 1531-1553. https://doi.org/10.1007/s10346-020-01556-7

Ji ZM, Hu SM, Chen ZJ, Niu QH, Wang TH, Wu FQ (2021) Laboratory investigation of the effect of the rotational speed on the coefficient of restitution. Eng Geol 292: 106196. https://doi.org/10.1016/j.enggeo.2021.106196

Jia Y, Zhu C, Wang D (2016) Marine geohazards: review and future perspective. Acta Geol Sin 90(4): 1455-1470. https://doi.org/10.1111/1755-6724.12779

Jongman RHG (2002) Homogeneisation and fragmentation of the European landscape: Ecological consequences and solutions. Landsc Urban Plan 58: 211-221. https://doi.org/10.1016/S0169-2046(01)00222-5

Kabisch N, Korn, H, Stadler J, Bonn A (2016) Nature-Based Solutions to Climate Change Adaptation in Urban Areas. Springer: Cham, Switzerland

Kenner R, Buhler Y, Delaloye R, Ginzler C, Phillips M (2014). Monitoring of high alpine mass movements combining laser scanning with digital airborne photogrammetry. Geomorphology 206: 492–504. https://doi.org/10.1016/j.geomorph.2013.10.020

Kumar P, Debele SE, Sahani J, Aragao L, Barisani F, Basu B, Bucchignani E, Charizopoulos N, Di Sabatino S, Domeneghetti A, Edo AS, Finér L, Gallotti G, Juch S, Leo LS, Loupis M, Mickovski SB, Panga D, Pavlova I, Pilla F, Prats AL, Renaud FG, Rutzinger M, Sarkar A, Shah MAR, Soini K, Stefanopoulou M, Toth E, Ukonmaanaho L, Vranic S, Zieher T (2020) towards an operationalization of nature-based solutions for natural hazards. Sci Total Environ 731: 138855. https://doi.org/10.1016/j.scitotenv.2020.138855

Kumar P, Debele SE, Jeetendra S, Rawat N, Marti-Cardona B, Alfieri SM, Basu B, Basu AS, Bowyer P, Charizopoulos N, Jaakko J, Loupis M, Menenti M, Mickovski SB, Pfeiffer J, Pilla F, Pröll J, Pulvirenti B, Rutzinger M, Sannigrahi S, Spyrou C, Tuomenvirta H, Vojinovic Z, Zieher T (2021) An overview of monitoring methods for assessing the performance of nature-based solutions against natural hazards. Earth Sci Rev 217: 103603. https://doi.org/10.1016/j.earscirev.2021.103603

Li X, Dong M, Jiang D, Li S, Shang Y (2020). The effect of surface roughness on normal restitution coefficient, adhesion force and friction coefficient of the particle-wall collision. Powder Technol 362: 17–25. https://doi.org/10.1016/j.powtec.2019.11.120

Margottini C, Spizzichino D (2021) Traditional Knowledge and Local Expertise in Landslide Risk Miti-gation of World Heritages Sites. In: Sassa K, Mikoš M, Sassa S, Bobrowsky PT, Takara K, Dang K (eds) Understanding and Reducing

Landslide Disaster Risk. WLF 2020. ICL Contribution to Landslide Disaster Risk Reduction. Springer, Cham. https://doi.org/10.1007/978-3-030-60196-634

Marinos P, Hoek E (2000) GSI: a geologically friendly tool for rock mass strength estimation. GeoEng2000, Technomic publ: 1422–1442.

Morales T, Clemente JA, Damas Mollá L, Izagirre E, Uriarte JA (2021) Analysis of instabilities in the Basque Coast Geopark coastal cliffs for its environmentally friendly management (Basque-Cantabrian basin, northern Spain). Eng Geol 283: 106023. https://doi.org/10.1016/j.enggeo.2021.106023

Naumann S, Kaphengst T, McFarland K, Stadler J (2014) Nature-based approaches for climate change mitigation and adaptation. In: The challenges of climate change – partnering with nature. German Federal Agency for Nature Conservation (BfN). Ecologic Institute, Bonn.

Paliaga G, Giostrella P, Faccini F (2016) Terraced landscape as cultural and environmental heritage at risk: an example from Portofino Park (Italy). Annales Ser Hist Sociol 26(3): 1-10. https://doi.org/10.19233/ASHS.2016.32

Paliaga G, Luino F, Turconi L, De Graff JV, Faccini F (2020) Terraced landscapes on Portofino Promontory (Italy): identification, geo-hydrological hazard and management. Water 12(2): 435. https://doi.org/10.3390/w12020435

Paliaga G, Luino F, Turconi L, Profeta M, Vojinovic Z, Cucchiaro S, Faccini F (2022) Terraces landscapes as NBSs for geo-hydrological hazard mitigation: towards a methodology for debris and soil volume estimations through a LiDAR survey. https://doi.org/10.3390/rs14153586

Palmstrom A (2005) Measurement of and correlations between block size and rock quality designation (RQD). Tunn Undergr Space Technol 20: 362–377. https://doi.org/10.1016/j.tust.2005.01.005

Pazzi V, Morelli S, Fanti R (2019) A review of the advantages and limitations of geophysical investigations in landslide studies. Int J Geophys: 2. https://doi.org/10.1155/2019/2983087

Perrone A, Canora F, Calamita G, Bellanova J, Serlenga V, Panebianco S, Tragni N, Piscitelli S, Doglioni A, Simeone V, Sdao F, Lapenna V (2021) A multidisciplinary approach for landslide residual risk assessment: the Pomarico landslide (Basilicata Region, Southern Italy) case study. Landslides 18: 353-365. https://doi.org/10.1007/s10346-020-01526-z

Pfeiffer T, Bowen TD (1989) Computer simulation of rockfalls. Bull Assoc Eng Geol 26: 135-146.

Pham BT, Pradhan B, Tien Bui D, Prakash I, Dholakia MB (2016) A comparative study of different machine learning methods for landslide susceptibility assessment: a case study of Uttarakhand area (India). Environ Model Softw 84: 240-250. https://doi.org/10.1016/j.envsoft.2016.07.005

Pontee N, Narayan S, Beck MW, Hosking AH (2016) Nature-based solutions: lessons from around the world. Inst Civ Eng Proc Marit Eng 169: 29–36. https://doi.org/10.1680/jmaen.15.00027

Prades-Valls A, Corominas J, Lantada N, Matas G, Núñez-Andrés MA (2022) Capturing rockfall kinematic and fragmentation parameters using high-speed camera system. Eng Geol 302: 106629. https://doi.org/10.1016/j.enggeo.2022.106629

Preti F, Errico A, Castelli G (2021) Terraced landscapes and hydrological-geological hazards: innovative approaches and future perspectives. Water 13(13): 1728. https://doi.org/10.3390/w13131728

Ratter BMW (2013). Surprise and uncertainty- Framing regional geohazards in the Theory of Complexity. Humanities 2: 1-19. https://doi.org/10.3390/h2010001

Rieg L, Wichmann V, Rutzinger M, Sailer R, Geist T, Stotter J (2014) Data infrastructure for multitemporal airborne LiDAR point cloud analysis—examples from physical geography in high mountain environments. Comput Environ Urban Syst 45:137–146. https://doi.org/10.1016/j.compenvurbsys.2013.11.004

Roccati A, Paliaga G, Luino F, Faccini F, Turconi L (2020) Rainfall Threshold for Shallow Landslides Initiation and Analysis of Long-Term Rainfall Trends in a Mediterranean Area. Atmosphere 11: 1367. https://doi.org/10.3390/atmos11121367

Roccati A, Paliaga G, Luino F, Faccini F, Turconi L (2021) GIS-Based Landslide Susceptibility Mapping for Land Use Planning and Risk Assessment. Land 10: 162. https://doi.org/10.3390/land10020162

Ruangpan L, Vojinovic Z, Di Sabatino S, Leo LS, Capobianco V, Oen AMP, McClain M, Lopez-Gunn E (2019) Nature-Based Solutions for hydro-meteorological risk reduction: A state-of-the-art review of the research area. Nat Hazards Earth Syst Sci Discuss https://doi.org/10.5194/nhess-2019-128

Sardana S, Sinha RK, Verma AK, Jaswal M, Singh TN (2022) A semi-empirical approach for rockfall prediction along the Lengpui-Aizawl highway Mizoram, India. Geotech Geol Eng. https://doi.org/10.1007/s10706-022-02229-z

Sarro R, Riquelme A, García-Davalillo JC, Mateos RM, Tomás R, Pastor JL, Cano M, Herrera G (2018) Rockfall simulation base don UAV photogrammetry data obtained during an emergency declaration: Application at a Cultural Heritage Site. Remote Sens 10(12): 1923. https://doi.org/10.3390/rs10121923

Shadabfar M, Mahsuli M, Zhang Y, Xue Y, Huang H (2022) Probabilistic data-driven framework for performance assessment of retaining walls against rockfalls. Probabilistic Eng Mech 70: 103339. https://doi.org/10.1016/j.probengmech.2022.103339

Spizzichino D, Margottini C, Chiessi V, Boldini D (2016) Assessment of the stability conditions of a large-volume sandstone block in the northern sector of the Siq of Petra. Landslides and Engineered Slopes. Experience, Theory and Practice: 1851 -1858

Tang J, Zhou X, Liang K, Lai Y, Zhou G, Tan J (2021) Experimental sutyd on the coefficient of restitution for the rotational sphere rockfall. Environ Earth Sci 80: 419. https://doi.org/10.1007/s12665-021-09684-6

Terranova R (1964) Le frane del Castellaro e di S.Rocco sul versante occidentale del Promontorio di Portofino. Atti Ist Geol Università di Genova: 342–376.

Terrone M, Paliaga G, Bazzurro N, Marchese A, Faccini F (2021) Groundwater resources in a fractured-rock aquifer, Conglomerate of Portofino, J Maps 17(2): 268-278. https://doi.org/10.1080/17445647.2021.1911868

Touili N, Baztan J, Vanderlinden JP, Kane IO, Diaz-Simal P, Pietrantoni L (2014) Public perception of engineering-based coastal flooding and erosion risk mitigation options: Lessons from three European coastal settings. Coast Eng 87: 205–209. https://doi.org/10.1016/j.coastaleng.2014.01.004

Turconi L, Faccini F, Marchese A, Paliaga G, Casazza M, Vojinovic Z, Luino F (2020) Implementation of Nature-Based Solutions for hydro-meteorological risk reduction in small mediterranean catchments: the case of Portofino Natural Regional Park, Italy. Sustainability 12(3): 1240. https://doi.org/10.3390/su12031240

Van der Meulen F, Ijff S, Van Zetten R (2022) Nature-based solutions for coastal adaptation management, concepts and scope, an overview. Nord J Bot: e03290. https://doi.org/10.1111/njb.03290

Villegas-Palacio C, Berrouet L, Marsiglia S (2020). Adaptive Capacity of Households to Degradation of Ecosystem Services: A Case Study in the Colombian Andes. Environ Management 66: 162–179. https://doi.org/10.1007/s00267-020-01305-5

Vojinovic Z, Keerakamolchai W, Torres AS, Weesakul S, Meesuk V, Alves A, Babel MS (2021) Towards holistic and multifunctional design of green and blue infrastructure for climate change adaptation in cultural heritage areas. In: Babel, M., Haarstrick, A., Ribbe, L., Shinde, V.R., Dichtl, D. (Eds.), Water Security in Asia - Opportunities and Challenges in the Context of Climate Change. Springer Water Series, Cham, pp 381-390. https://doi.org/10.1007/978-3-319-54612-4_28

Volkwein A, Schellenberg K, Labiouse V, Agliardi F, Berger F, Bourrier F, Dorren LKA, Gerber W, Jaboyedoff M (2011). Rockfall characterisation and structural protection – a review. Nat Hazards Earth Syst Sci 11: 2617–2651. https://doi.org/10.5194/nhess-11-2617-2011

Wang L, Zheng Z, Yu Y, Liu T, Zhang Z (2020). Determination of the energetic coefficient of restitution of maize grain based on laboratory experiments and DEM simulations. Powder Technol 362: 645–658. https://doi.org/10.1016/j.powtec.2019.12.024

Ye Y, Zeng Y, Chen X, Sun H, Ma W, Peng Z (2021) Development of a viscoelastoplastic contact model for the size- and velocity-dependent normal restitution coefficient of a rock sphere upon impact. Comput Geotech 132: 104014. https://doi.org/10.1016/j.compgeo.2021.104014

Zhang JY, Li HB, Yang XG, Jiang N, Zhou JW (2021). Quantitative assessment of rockfall hazard in post-landslide high rock slope through terrestrial laser scanning. Bull Eng Geol Environ 80(10): 7315-7331. https://doi.org/10.1007/s10064-021-02426-9

5. Discusión

Barrera de protección en el Geoparque de Zumaia

5. Discusión

La presente tesis avanza en estrategias de adaptación al riesgo de caída de rocas desde acantilados costeros en espacios litorales con notable actividad humana. En este sentido, la gestión actual del territorio requiere el desarrollo de enfoques innovadores que garanticen la conservación de los espacios y dinámicas naturales, y beneficien a la sociedad, mitigando los riesgos y aumentando la resiliencia (Pontee et al., 2016; Castelle et al., 2019; Villegas-Palacio et al., 2020), mediante estrategias de bajo impacto y mínimamente invasivas (“friendly”) (Domínguez-Cuesta et al., 2022), acordes con las directrices de las Nature-Based Solutions (NBSs) (Kumar et al., 2021; Vojinovic et al., 2021).

Esta forma de aproximación requiere profundizar en conocimientos de detalle del entorno de estudio y de sus condicionantes dinámicos (Pradhan, 2011; Chen et al., 2013; Pham et al., 2016).

En el contexto de estudio, el alcance espacial delimitado de los procesos de caída de rocas en un marco geomorfológico bien definido, facilita la obtención de medidas directas en los afloramientos rocosos del frente de los acantilados, la identificación y caracterización de trayectorias de caídas, características dimensionales y alcance de los bloques desprendidos (Masuya et al., 2009; Lorentz et al., 2010; Lambert and Bourrier, 2013).

En lo que se refiere a la tipología y dimensiones de los desprendimientos, quedan determinadas por las propiedades geomecánicas de los materiales, las características de la red de discontinuidades y su orientación respecto a los acantilados (Cai et al., 2004; Kim et al., 2007; Morelli, 2016; Corominas et al., 2017).

En la Costa Vasca (capítulos I, II, III y IV), la naturaleza flyschoide de los materiales ha dado lugar, por erosión diferencial, a una sucesión de entrantes y salientes de distintas dimensiones, en los que la tipología de caídas está condicionada, principalmente, por la orientación de los planos de estratificación respecto a los taludes de los acantilados. En este sentido, la estratificación es la familia de discontinuidad más marcada y que presenta un mayor desarrollo superficial (superior a los 10 metros), mientras en el resto de discontinuidades, en gran medida ortogonales a la estratificación, registran un desarrollo que se limita básicamente a la potencia de los estratos. Como consecuencia, la caída de rocas de tamaño moderado que llegan a alcanzar la playa es un proceso recurrente que supone un riesgo para usuarios y visitantes. Los bloques desprendidos, en general inferiores a 0,2 m^3, presentan formas paralelepípedas (Leine et al., 2013; Farvacque et al., 2019; Mavrouli and Corominas, 2020), con ángulos entre planos próximos a 90º, característicos de entornos flyschoides (Marinos and Hoek, 2001), y muestran una frecuencia inversamente proporcional a su tamaño.

En los casos en los que la orientación de la estratificación es paralela a los acantilados, se registran inestabilidades menos frecuentes, con roturas asimilables al tipo talud infinito (Matos, 2020) y vuelcos, que llegan a alcanzar dimensiones de desarrollo métrico. La distribución de tamaño de bloques muestra un carácter de conjunto del tipo “power law” (capítulos I y II), asimilable a la obtenida por otros autores (Hovius et al., 1997; Pelletier et al., 1997; Guzzetti et al., 2002; Corominas et al., 2017).

Cuando el análisis se centra en zonas concretas de alta actividad, las distribuciones censuradas por encima de un valor mínimo muestran un carácter normal (capítulo I), en la medida en que los bloques desprendidos provienen mayoritariamente de los estratos más competentes de la serie (caliza, margocaliza, arenisca).

Respecto a la formación conglomerática de Portofino (capítulo V), las roturas se desarrollan de manera más irregular. Los bloques presentan morfologías esféricas (Asteriou and Tsiambaos 2018; Chen et al., 2019), con tamaños medios de 1 m^3 y máximos registrados de hasta 3 m^3 en los últimos años, que llegan a impactar en las poblaciones locales (Turconi et al., 2020).

En lo que se refiere al análisis de caída de rocas, los modelos numéricos 3D permiten considerar procesos de dispersión lateral en la generación de trayectorias, incluyendo los efectos geométricos de la topografía en su dinámica (Sarro et al., 2018; Fanos y Pradhan, 2019), superando así las limitaciones de los modelos 2D (Volkwein et al., 2011). En nuestro trabajo, se parte de modelos digitales del terreno (MDT) de alta resolución obtenidos mediante fotogrametría con vehículo aéreo no tripulado (Itzurun, capítulo I), Láser Escáner Terrestre (Atxabiribil, Punta Begoña y Barinatxe, capítulos II, III y IV) y LiDAR satelital (Portofino, capítulo V), en función de las condiciones geomorfológicas del entorno y las restricciones de utilización (Delmonaco et al., 2015; Frodella et al., 2016), que representan de modo realista el relieve original (Dorren, 2003; Lan et al., 2007; Stoffel et al., 2010; Keskin, 2013; Ansari et al., 2018) y facilitan combinar la información mediante georreferenciación (Adam et al., 2002; Bruyninx et al., 2019). En el caso de Portofino, se dispuso de información correspondiente a los años 2008 y 2020, lo que permitió además valorar la evolución espacial de los procesos de erosión y depósito en la zona de estudio durante este intervalo de tiempo.

Las nubes de puntos obtenidas, son la base para generar mallas tridimensionales de las zonas de estudio con las que modelizar la caída de rocas, en nuestro caso mediante un enfoque de cuerpo rígido ("rigid body approach") que incluye la forma y tamaño de los bloques desprendidos. Este enfoque considera el impacto del bloque sobre la superficie del suelo como un fenómeno casi instantáneo durante el cual el movimiento es nulo. Para ello se utiliza fundamentalmente el software RocPro3D (RocPro3D, 2018), que permite incorporar una aproximación probabilística con variaciones en la forma de los bloques, características de los suelos e irregularidades del terreno. El impacto queda caracterizado por la disipación de energía, que tiene en cuenta los coeficientes de restitución Rn (restitución normal) y Rt (restitución tangencial), que son los parámetros más utilizados en los estudios de caída de rocas (Pfeiffer and Bowen, 1989; Bourrier et al., 2012; Wang et al., 2014; Asteriou and Tsiambaos, 2018; Li et al., 2020; Tang et al., 2021). En nuestro caso, estos parámetros se obtienen para cada terreno diferenciado por ajuste (back-analysis), reproduciendo las trayectorias y alcance de los fragmentos de roca reconocidos (ground-truthed). En trabajos futuros, se considera la posibilidad de revisar estos valores mediante determinaciones experimentales adicionales en campo y laboratorio que permitan verificar y precisar los resultados (Bourrier et al., 2012; Asteriou and Tsiambaos, 2018; Ji et al., 2020).

Tras el proceso de calibración, los análisis de susceptibilidad a la caída de rocas de los entornos de estudio aportan la información espacial necesaria para el desarrollo de estrategias de gestión. La modelización se centra, prioritariamente, en los bloques de roca de mayor tamaño, ya que constituyen el peor escenario de seguridad cuando permanecen intactos mientras se desplazan ladera abajo (Pfeiffer y Bowen, 1989), alcanzando la mayor energía (Corominas et al., 2017). En este sentido, el tamaño de los bloques desprendidos es uno de los principales factores que controlan la trayectoria de caída (Hungr et al., 1999; Okura et al., 2000) y queda definido por el espesor de los estratos rocosos más competentes y la persistencia y separación de las familias de discontinuidades (Cai et al., 2004; Palmstrom, 2005; Cooke et al, 2006; Kim et al., 2007; Morelli, 2016; McGinnis et al., 2017). En este punto la definición y determinación del mayor evento creíble de caída de rocas (“largest credible volume”), que no el mayor evento concebible, es un reto que futuras investigaciones tendrán que abordar para concretar y perfeccionar el diseño de medidas y la delimitación de zonas de riesgo (Abbruzzese et al., 2009; Agliardi et al., 2009; Li et al., 2009; Corominas et al., 2017).

En el caso de Itzurun (capítulo I), dado que las distribuciones por zonas de los principales bloques depositados en la base de los taludes de los acantilados se ajustan a funciones de densidad normal, el tamaño del bloque considerado para el diseño corresponde al 95% de la distribución (como valor característico superior, Bond y Harris, 2008).

A partir de los análisis de susceptibilidad, se avanzan las propuestas de gestión y protección específicas para cada entorno de estudio, en función del alcance y energía de impacto de las caídas de roca (Volkwein et al., 2011). En nuestro caso, dado el alto valor reconocido de los litorales de la Costa Vasca y Liguria, las estrategias de gestión buscan minimizar el riesgo mediante actuaciones proporcionales, que garanticen la conservación de los espacios y dinámicas naturales (Andrasanu, 2009; Wimbledon and Smith-Meyer, 2012; Brilha, 2018; Accastello et al., 2019; Castelle et al., 2019; Van der Meulen et al., 2022). Para ello, se desarrollan propuestas de gestión que priorizan las actuaciones de prevención, señalización e información (capítulos I, II, III, IV y V) y que se combinan con actuaciones locales de bajo impacto (friendly) en las zonas en que sea recomendable (capítulos I y V), seguimiento de movimientos extremadamente lentos del terreno mediante dispositivos de control geotécnico permanente (capítulo III) y elementos de protección basados en la naturaleza (NBSs; capítulos II y IV), cuya eficacia es revisada en los modelos dinámicos.

En conjunto, en el presente trabajo se ha desarrollado una aproximación conceptual y metodológica que sirve de base para avanzar en el desarrollo de estrategias de gestión adaptadas a entornos de alto valor medioambiental, cultural y paisajístico frente a riesgos geológicos, y que puede ser ampliada y validada en otros entornos, no solo litorales.

5.1. Discussion

This thesis advances in adaptation strategies to the risk of rockfall from coastal cliffs in coastal areas with significant human activity. In this sense, current land management requires the development of innovative approaches that ensure the conservation of natural spaces and dynamics, and benefit society, mitigating risks and increasing resilience (Pontee et al., 2016; Castelle et al., 2019; Villegas-Palacio et al., 2020), through low-impact and minimally invasive (friendly) strategies (Domínguez-Cuesta et al., 2022), in line with Nature-Based Solutions (NBSs) guidelines (Kumar et al., 2021; Vojinovic et al., 2021).

This form of approach requires deepening detailed knowledge of the study environment and its dynamic constraints (Pradhan, 2011; Chen et al., 2013; Pham et al., 2016).

In the study context, the delimited spatial extent of the rockfall processes in a well-defined geomorphological setting facilitates obtaining direct measurements on the rocky outcrops of the cliff face, identification and characterization of fall trajectories, dimensional characteristics and extent of detached blocks (Masuya et al., 2009; Lorentz et al., 2010; Lambert and Bourrier, 2013).

Regarding the typology and dimensions of detachments, they are determined by the geomechanical properties of the materials, the characteristics of the discontinuity network and its orientation with respect to the cliffs (Cai et al., 2004; Kim et al., 2007; Morelli, 2016; Corominas et al., 2017).

On the Basque Coast (chapters I, II, III and IV), the flyschoid nature of the materials has given rise, by differential erosion, to a succession of inlets and ledges of different dimensions, in which the type of falls is mainly conditioned by the orientation of the stratification planes with respect to the cliff slopes. In this sense, stratification is the most marked family of discontinuities with the greatest surface development (greater than 10 meters), while the rest of the discontinuities, largely orthogonal to the stratification, show a development that is basically limited to the strength of the strata. Therefore, the fall of moderate-sized rocks that reach the beach is a recurrent process that poses a risk to users and visitors. The detached blocks, generally smaller than 0.2 m^3, present parallelepiped shapes (Leine et al., 2013; Farvacque et al., 2019; Mavrouli and Corominas, 2020), with inter-plane angles close to 90º, characteristic of flyschoid environments (Marinos and Hoek, 2001), and show a frequency inversely proportional to their size.

In cases where the orientation of the stratification is parallel to the cliffs, less frequent instabilities are recorded, with breaks comparable to the infinite slope type (Matos, 2020) and toppling, which can reach metric dimensions. The block size distribution shows a set character of the "power law" type (chapters I and II), assimilable to that obtained by other authors (Hovius et al., 1997; Pelletier et al., 1997; Guzzetti et al., 2002; Corominas et al., 2017).

When the analysis is focused on specific zones of high activity, the censored distributions above a minimum value show a normal character (chapter I), insofar as the detached blocks come mostly from the most competent strata of the series (limestone, marlstone, sandstone).

With respect to the Portofino conglomeratic formation (chapter V), the breaks are more irregularly developed. The blocks present spherical morphologies (Asteriou and Tsiambaos 2018; Chen et al., 2019), with average sizes of 1 m^3 and maximum recorded of up to 3 m^3 in recent years, which come to impact local populations (Turconi et al., 2020).

Regarding rockfall analysis, 3D numerical models allow considering lateral dispersion processes in the generation of trajectories, including the geometrical effects of topography on their dynamics (Sarro et al., 2018; Fanos and Pradhan, 2019), thus overcoming the limitations of 2D models (Volkwein et al., 2011). In our work, we start from high-resolution digital terrain models (DTM) obtained by unmanned aerial vehicle photogrammetry (Itzurun, chapter I), Terrestrial Laser Scanner (Atxabiribil, Punta Begoña and Barinatxe, chapters II, III and IV) and satellite LiDAR (Portofino, chapter V), depending on the geomorphological conditions of the environment and use restrictions (Delmonaco et al., 2015; Frodella et al., 2016), with which to realistically represent the original relief (Dorren, 2003; Lan et al., 2007; Stoffel et al., 2010; Keskin, 2013; Ansari et al., 2018) and to combine the information by georeferencing (Adam et al., 2002;

Bruyninx et al., 2019). In the case of Portofino, information was available for the years 2008 and 2020, which also allowed us to assess the spatial evolution of erosion and deposition processes in the study area during this time interval.

The point clouds obtained are the basis for generating three-dimensional meshes of the study areas with which to model the rockfall, in our case using a rigid body approach. This approach considers the impact of the block on the ground surface as an almost instantaneous phenomenon during which the movement is nil. For this purpose, the RocPro3D software (RocPro3D, 2018) was used primarily, which allows incorporating a probabilistic approach with variations in block shape, soil characteristics and terrain irregularities. The impact is characterized by the energy dissipation, which takes into account the restitution coefficients Rn (normal restitution) and Rt (tangential restitution), which are the most commonly used parameters in rockfall studies (Pfeiffer and Bowen, 1989; Bourrier et al., 2012; Wang et al., 2014; Asteriou and Tsiambaos, 2018; Li et al., 2020; Tang et al., 2021). In our case, these parameters are obtained for each ground differentiated by adjustment (back-analysis), reproducing the trajectories and runout of the recognized rock fragments (ground-truthed). In future work, we consider the possibility of revising these values by additional experimental determinations in field and laboratory to verify and refine the results (Bourrier et al., 2012; Asteriou and Tsiambaos, 2018; Ji et al., 2020).

Following the calibration process, rockfall susceptibility analyses of the study environments provide the spatial information necessary for the development of management strategies. The modeling focuses on the larger rock blocks, as they constitute the worst-case safety scenario when they remain intact while moving downslope (Pfeiffer and Bowen, 1989), reaching the highest energy (Corominas et al., 2017). In this sense, the size of detached blocks is one of the main factors controlling the fall trajectory (Hungr et al., 1999; Okura et al., 2000) and is defined by the thickness of the most competent rock strata and the persistence and separation of discontinuity families (Cai et al., 2004; Palmstrom, 2005; Cooke et al, 2006; Kim et al., 2007; Morelli, 2016; Corominas et al., 2017; McGinnis et al., 2017). At this point the definition and determination of the largest credible rockfall event ("largest credible volume"), which is not the largest conceivable event, is a challenge that future research will have to address in order to concretize and refine the design of measures and the delimitation of risk zones (Abbruzzese et al., 2009; Agliardi et al., 2009; Li et al., 2009; Corominas et al., 2017).

In the case of Itzurun (chapter I), since the zonal distributions of the main blocks deposited at the base of the cliff slopes conform to normal density functions, the block size considered for the design corresponds to 95% of the distribution (as upper characteristic value, Bond and Harris, 2008).

Susceptibility analyses allow specific management and protection proposals to be made for each study environment, depending on the runout and impact energy of rockfalls (Volkwein et al., 2011). In our case, given the recognized high value of the coastlines of the Basque and Ligurian coasts, the management strategies seek to minimize the risk through proportional actions that guarantee the conservation of natural spaces and dynamics (Andrasanu, 2009; Wimbledon and Smith-Meyer, 2012; Brilha, 2018; Accastello et al., 2019; Castelle et al., 2019; Van der Meulen et al., 2022). To this end, management proposals are developed that prioritize prevention, signaling and information actions (chapters I, II, III, IV and V) and that are combined with low-impact local actions (friendly) in areas where it is advisable (chapters I and V), monitoring of extremely slow ground movements through permanent geotechnical control devices (chapter III) and nature-based protection elements (NBSs; chapters II and IV), whose effectiveness is reviewed in the dynamic models.

Overall, this work has developed a conceptual and methodological approach that serves as a basis for advancing in the development of management strategies adapted to environments of high environmental, cultural and landscape value in the face of geological hazards, and that can be extended and validated in other environments, not only coastal.

5.2. Eztabaida

Tesi hau giza jarduera nabarmena duten itsasertzetan kostako labarretatik arrokak erortzeko arriskura moldatzeko estrategietan aurrerakuntzak eskaintzen ditu. Alde horretatik, lurraldearen egungo kudeaketak ikuspegi berritzaileak garatzea eskatzen du, espazio eta dinamika naturalen kontserbazioa bermatuko dituztenak eta gizarteari mesede egingo diotenak, arriskuak arinduz eta erresilientzia handituz (Pontee et al., 2016; Castelle et al., 2019; Villegas-Palacio et al., 2020), inpaktu txikiko eta inbasio minimoko estrategien bidez (Domínguez-Cuesta et al., 2022), Nature-Based Solutions-en arautegiarekin bat datozenak (Kumar et al., 2021; Vojinovic et al., 2021).

Hurbiltze-modu horrek azterketa-ingurunearen eta haren baldintza dinamikoen xehetasunetan sakontzea eskatzen du (Pradhan, 2011; Chen et al., 2013; Pham et al., 2016).

Azterketaren testuinguruan, ondo zehaztutako esparru geomorfologiko batean izanda, arrokak erortzeko prozesuek espazioan duten irismena kalkulatu daitezke, neurri zuzenak labarren fronteko arroka-azalemenduetan, erorketen ibilbideak, dimentsio-ezaugarriak eta eroritako blokeen irismena identifikatuz eta karakterizatuz (Masuya et al., 2009; Lorentz et al., 2010; Lambert and Bourrier, 2013).

Erorketen tipologiari eta neurriei dagokienez, materialen propietate geomekanikoek, etengune-sarearen ezaugarriek eta itsaslabarrekiko orientazioak zehazten dituzte (Cai et al., 2004; Kim et al., 2007; Morelli, 2016; Corominas et al., 2017).

Euskal Kostan (I., II., III. eta IV. kapituluak), materialen izaera flyschoideak, higadura-diferentzialaren ondorioz, hainbat dimentsiotako sarguneak eta irtenguneak sortu ditu; horietan, erorketen tipologia, batez ere, estratifikazio-planoek itsaslabarretako ezpondekiko duten orientazioaren mende dago. Alde horretatik, estratifikazioa jarraitutasun handieneko familia markatuena da, eta azalera-garapen handiena du (10-metrotik gorakoa); gainerako etenguneak, berriz, estratifikazioarekiko neurri handi batean ortogonalak, estratuen potentziara mugatzen den garapena dute. Ondorioz, hondartzara iristen diren tamaina ertaineko arroken erorketa prozesu errepikaria da, eta arriskutsua da erabiltzaileentzat eta bisitarientzat. Eroritako blokeek, oro har, 0,2 m^3 baino txikiagoak, forma paralelepipedoak dituzte (Leine et al., 2013; Farvacque et al., 2019; Mavrouli and Corominas, 2020), 90ºtik hurbil dauden planoen arteko angeluak dituztenak, ingurune flyschoideen bereizgarriak direnak (Marinos and Hoek, 2001), eta tamainaren alderantzizko maiztasuna dute.

Estratifikazioaren orientazioa itsaslabarrekiko paraleloa den kasuetan, ezegonkortasun ez hain ohikoak garatzen dira dira, ezponda mugagabe motako hausturekin (Matos, 2020) eta iraulketekin, garapen metrikoko dimentsioetara iristen direnak. Blokeen tamainaren banaketak "power law" motako baterako izaera erakusten du (I. eta II. kapituluak), beste autore batzuek lortutakoarekin parekagarria (Hovius et al., 1997; Pelletier et al., 1997; Guzzetti et al., 2002; Corominas et al., 2017).

Analisia jarduera handiko eremu zehatzetan oinarritzen denean, balio minimo baten gainetik zentsuratutako banaketek izaera normala erakusten dute (I. kapitulua), askatutako blokeak serieko estratu erresistenteagoetatik (kareharria, kareharri tupatsua, hareharria) datozelako nagusiki.

Portofinoren izaera konglomeratikoari dagokionez (V. kapitulua), hausturak modu irregularragoan garatzen dira. Blokeek morfologia esferikoak dituzte (Asteriou and Tsiambaos

2018; Chen et al., 2019). Batez besteko neurriak 1 m^3 dira, gehienezko 3 m^3 izan daitezkenak, azken urteotan eragina izan dituztenak tokiko populazioetan (Turconi et al., 2020).

Arroken erorketaren azterketari dagokionez, 3D zenbakizko ereduek aukera ematen dute ibilbideak sortzeko alboko sakabanatze-prozesuak kontuan hartuta, topografiak bere dinamikan dituen ondorio geometrikoak barne (Sarro et al., 2018; Fanos eta Pradhan, 2019), eta, hala, 2D ereduen mugak gaindituz (Volkwein et al., 2011). Gure lanean, bereizmen handiko lurzoruaren eredu digitaletatik (MDT) abiatzen gara. Eredu horiek fotogrametriaren bidez lortzen dira, tripulatu gabeko aire-ibilgailuekin (Itzurun, I. kapitulua), Lurreko Laser Eskanerrarekin (Atxabiribil, Punta Begoña eta Barinatxe, II., III. eta IV. kapituluak) eta LiDAR sateliteekin (Portofino, V. kapitulua), ingurunearen baldintza geomorfologikoen eta erabilera-mugen arabera (Delmonaco et al., 2015; Frodella et al., 2016), jatorrizko erliebea modu errealistan irudikatzeko (Dorren, 2003; Lan et al., 2007; Stoffel et al., 2010; Keskin, 2013; Ansari et al., 2018) eta informazioa geoerreferentziazioaren bidez konbinatzeko (Adam et al., 2002; Bruyninx et al., 2019). Portofinoren kasuan, 2008. eta 2020. urteetako informazioa jaso zen, eta, horri esker, gainera, denbora-tarte horretan eremuko higadura- eta metatze-prozesuen bilakaera espaziala baloratu ahal izan zen.

Lortutako puntu-hodeiak harri-jausiak modelizatzeko azterketa-eremuetako hiru dimentsioko sareak sortzeko oinarria dira, gure kasuan, gorputz zurruneko ikuspegi baten bidez (“rigid body approach”). Ikuspegi horren arabera, blokeak lurzoruaren gainazalean duen eragina ia bat-bateko fenomeno gisa hartzen da, eta mugimendu nulua izaten du. Horretarako, batez ere RocPro3D softwarea erabili da (RocPro3D, 2018). Horren bidez, hurbilketa probabilistikoa egin daiteke, blokeen forma-aldaketak, lurzoruen ezaugarriak eta lurzoruaren irregulartasunak kontuan hartuta. Inpaktuaren ezaugarria energia xahutzea da, Rn leheneratze-koefizienteak (leheneratze normala) eta Rt koefizienteak (leheneratze tangentziala) kontuan hartuta, horiek baitira arroken erorketa-azterketetan gehien erabiltzen diren parametroak (Pfeiffer and Bowen, 1989; Bourrier et al., 2012; Wang et al., 2014; Asteriou andTsiambaos, 2018; Li et al., 2020; Tang et al., 2021). Gure kasuan, parametro horiek doikuntzaz bereizitako lurzoru bakoitzerako lortzen dira (back-analysis), eta ezagutzen diren arroka zatien (ground-truthed) ibilbideak eta irismena erreproduzitzen dira. Etorkizuneko lanetan, balio horiek landako eta laborategiko esperimentu-determinazio gehigarrien bidez berrikusteko aukera aztertzen da, emaitzak egiaztatu eta doitzeko (Bourrier et al., 2012; Asteriou and Tsiambaos, 2018; Ji et al., 2020).

Kalibrazio-prozesuaren ondoren, azterketa-inguruneetako arrokak erortzeko suszeptibilitate-analisiek kudeaketa-estrategiak garatzeko behar den informazio espaziala ematen dute. Modelizazioa tamaina handiagoko arroka-blokeetan oinarritzen da, ezpondan behera mugitzen diren bitartean (Pfeiffer eta Bowen, 1989) segurtasun-egoerarik okerrena osatzen baitute, energia handiena lortuz (Corominas et al., 2017). Alde horretatik, erorketa-ibilbidea kontrolatzen duten faktore nagusietako bat askatutako blokeen tamaina da (Hungr et al., 1999; Okura et al., 2000), eta honako hauek definitzen dute: arroka-estratu konpetenteen potentzia eta etengune-familien jarraitutasuna eta bereizketa (Cai et al., 2004; Palmstrom, 2005; Cooke et al, 2006; Kim et al., 2007; Morelli, 2016; Corominas et al., 2017; McGinnis et al., 2017). Puntu horretan, arrokak erortzeko gertaera sinesgarririk handiena definitzea eta zehaztea (“largest credible volume”), pentsa daitekeen gertaerarik handiena ez dena, etorkizuneko ikerketek egin beharko duten erronka bat da, neurrien diseinua eta arrisku-eremuen mugaketa zehazteko eta hobetzeko (Abbruzzese et al., 2009; Agliardi et al., 2009; Li et al., 2009; Corominas et al., 2017).

Itzurunen kasuan (I. kapitulua), itsaslabarretako ezponden oinarrian dauden bloke nagusien zonakako banaketak dentsitate normaleko funtzioetara doitzen direnez, diseinurako kontuan hartutako blokearen tamaina banaketaren %95i dagokio (goiko balio bereizgarri gisa, Bond eta Harris, 2008).

Suszeptibilitate-analisien bidez, ikerketa-ingurune bakoitzerako berariazko kudeaketa- eta babes-proposamenak egin daitezke, harri-jausien irismenaren eta inpaktu-energiaren arabera (Volkwein et al., 2011). Gure kasuan, Euskal Kostaldeko eta Liguriako itsasertzek balio altuko inguruneak direnez, kudeaketa-estrategien helburua arriskua minimizatzea da, jarduera proportzionalen bidez, espazio eta dinamika naturalen kontserbazioa bermatzeko (Andrasanu, 2009; Wimbledon and Smith-Meyer, 2012; Brilha, 2018; Accastello et al., 2019; Castelle et al., 2019; Van der Meulen et al., 2022). Horretarako, prebentzio-, seinaleztapen- eta informazio-jarduerei lehentasuna ematen dieten kudeaketa-proposamenak garatzen dira (I., II., III., IV. eta V. kapituluak), inpaktu txikiko (friendly) tokiko jarduerekin konbinatzen direnak, hala komeni den eremuetan (I. eta V. kapituluak), lurzoruaren mugimendu oso motelen jarraipena eginez, kontrol geoteknikoko gailu iraunkorren bidez (III. kapitulua) eta naturan oinarritutako babes-elementuak garatuz (NBSak; II. eta IV. kapituluak). Horien eraginkortasuna eredu dinamikoetan berrikusten da.

Oro har, lan honetan, hurbilketa kontzeptual eta metodologiko bat garatu da, ingurumen-, kultura- eta paisaia-balio handiko inguruneetara arrisku geologikoen aurrean egokitutako kudeaketa-estrategien garapenean aurrera egiteko oinarri gisa balio duena, beste ingurune batzuetara, ez bakarrik itsasertzean, zabaldu eta balidatu daitekeena.

6. Conclusiones

Arcos del acantilado de Zumaia

6. Conclusiones

La gestión de los espacios costeros que a nivel mundial mantienen un alto valor paisajístico, natural y cultural, y que reciben un elevado número de visitantes, como los litorales de la Costa Vasca y Liguria, requieren la elaboración de estrategias de gestión específicas. Estas estrategias deben permitir evaluar la susceptibilidad al desarrollo de procesos de inestabilidad (como movimientos del terreno o caídas de rocas) en detalle, con el objetivo de desarrollar planes de gestión minimamente invasivos, que garanticen la seguridad de los espacios, acordes a las directrices de las Nature-Based Solutions (NBSs).

En este contexto, la presente tesis doctoral aborda la problemática de los riesgos geológicos, principalmente caídas de rocas en los capítulos I, II, IV y V y movimientos del terreno en el III, que se corresponden con los afloramientos rocosos de los acantilados costeros. En estos casos, tanto la información topográfica detallada como la caracterización directa en campo sobre los procesos de desprendimiento de rocas permiten desarrollar modelos 3D detallados, con los que realizar análisis de susceptibilidad que definan el alcance y la energía máxima de los bloques desprendidos.

A partir de estas informaciones, se pueden proponer estrategias de gestión medioambientalmente sostenibles, ajustadas a cada espacio estudiado, con los siguientes objetivos prioritarios: que sean eficaces, para resolver el problema; mínimamente invasivas, para preservar el carácter natural del entorno; proporcionales, de acuerdo con los objetivos de seguridad establecidos; y reversibles, para garantizar la durabilidad del entorno. Estos objetivos base, unidos al desarrollo de actuaciones focalizadas en las NBSs, darán lugar a espacios más naturales y seguros para los usuarios, que permitan su uso y disfrute.

Este enfoque integral ha sido contrastado en la playa de Itzurun en el Geoparque de la Costa Vasca (capítulo I), playa de Atxabiribil (capítulo II), Galerías Punta Begoña (capítulo III), playa de Barinatxe (capítulo IV) y costa de Portofino (capítulo V). Estos estudios complementarios pueden ser aplicables en diferentes entornos geomorfológicos espacialmente bien definidos, no necesariamente costeros, con procesos de inestabilidad similares, especialmente en zonas de acantilados en entornos con altos índices de ocupación y uso.

6.1. Conclusions

The management of coastal areas that maintain a high landscape, natural and cultural value throughout the world, and that receive a high number of visitors (more than 1 million) each year, such as the coastlines of the Basque Coast and Portofino, requires the development of specific analysis strategies. These strategies should allow to evaluate the susceptibility to develop instability processes (such as ground movements or rock falls) in detail, with the aim of developing minimally invasive management tactics, which guarantee the safety of the spaces and are based on the guidelines of the Nature-Based Solutions (NBSs).

In this context, this doctoral thesis addresses the problem of geological hazards, mainly rockfalls in chapters I, II, IV and V and ground movements in Chapter III, which correspond to the rocky outcrops of coastal cliffs. In all these cases, both the detailed topographic information and the direct field characterization of rockfall processes allows the development of detailed 3D model for susceptibility analysis, that define the runout and maximum energy of the detached blocks.

Based on this information, friendly management strategies can be proposed, tailored to each area studied, with the following priority objectives: effective, to solve the problem; minimally invasive, to preserve the natural character of the environment; proportional, in accordance with the established safety objectives; and reversible, to guarantee the durability of the environment.

These basic objectives, together with the development of actions focused on the NBSs, will result in more natural and safer spaces for users, allowing their use and enjoyment.

This integrated approach verified at Itzurun beach in the Basque Coast Geopark (chapter I), Atxabiribil beach (chapter II), Galerías Punta Begoña (chapter III), Barinatxe beach (chapter IV) and Portofino coast (chapter V). These complementary studies can be useful in different spatially well-defined geomorphological environments, not necessarily coastal, with similar instability processes, especially cliffs in environments with high rates of occupation and use.

6.2. Ondorioak

Munduan zehar paisaia-, natura- eta kultura-balio handia duten eta urtero bisitari ugari (milioi 1 baino gehiago) jasotzen dituzten itsasertzeko espazioen kudeaketak, hala nola Euskal Kostaldeko eta Portofinoko itsasertzekoak, analisi-estrategia espezifikoak lantzea eskatzen du. Estrategia horiek aukera eman behar dute ezegonkortasun-prozesuak (hala nola lurraren mugimenduak edo arroken erorketak) xehetasunez garatzeko sentikortasuna ebaluatzeko, gutxieneko kudeaketa-taktika inbaditzaileak garatzeko helburuarekin, espazioen segurtasuna bermatuko dutenak eta Naturan Oinarritutako Irtenbide (NBS) delakoen jarraibideetan oinarritutak egongo direnak.

Testuinguru horretan, doktorego-tesi honek arrisku geologikoen problematika jorratzen du, batez ere I., II., IV. eta V. kapituluetako arroka-erorketak eta III. kapituluko lur-mugimenduak, kostaldeko labarretako arroka-azaleratzeekin bat datozenak. Kasu horietan guztietan, bai informazio topografiko xehatuak, bai harrien luizi-prozesuen landa-karakterizazio zuzenak aukera ematen dute 3D eredu xehatuak garatzeko, eta horietatik abiatuta, jaregindako blokeen irismena eta gehieneko energia definituko duten suszeptibilitate-analisiak ezartzeko.

Informazio horietatik abiatuta, kudeaketa-estrategia lagunkoiak proposa daitezke, aztertutako espazio bakoitzera egokituak, lehentasunezko helburu hauekin: eraginkorrak izatea, arazoa konpontzeko; inbaditzaileak ez izatea, ingurunearen izaera naturala babesteko; proportzionalak, ezarritako segurtasun-helburuen arabera; eta itzulgarriak, ingurunearen iraunkortasuna bermatzeko. Oinarrizko helburu horiek, NBSetan ardaztutako jardueren garapenarekin batera, espazio naturalagoak eta seguruagoak sortuko dituzte erabiltzaileentzat, haien erabilera eta gozamena ahalbidetzeko.

Ikuspegi integral hori Itzurungo hondartzan, Euskal Kostaldeko Geoparkean (I. kapitulua), Atxabiribilgo hondartzan (II. kapitulua), Punta Begoñako galerietan (III. kapitulua), Barinatxeko hondartzan (IV. kapitulua) eta Portofinoko kostaldean (V. kapitulua) berretsi da. Azterlan osagarri horiek erabilgarriak izan daitezke espazioari dagokionez ondo definitutako hainbat ingurune geomorfologikotan, ez ezinbestean itsasertzekoak, antzeko ezegonkortasun-prozesuekin, bereziki erabilera eta okupazio-tasa altua daukaten horietan.

Referencias-References-Bibliografia

Abbruzzese, J.M., Sauthier, C., Labiouse, V. (2009). Considerations on Swiss methodologies for rock fall hazard mapping base don trajectory modelling. Nat. Hazards Earth Syst. Sci. 9(4): 1095-1109. https://doi.org/10.5194/nhess-9-1095-2009

Abellán, A., Calvet, J., Vilaplana, J.M., Blanchard, J. (2010). Detection and spatial prediction of rockfalls by means of terrestrial laser scanner monitoring. Geomorphology 119: 162-171. https://doi.org/10.1016/j.geomorph.2010.03.016

Abellán, A., Oppikofer, T., Jaboyedoff, M., Rosser, N.J., Lim, M., Lato, M.J. (2014). Terrestrial laser scanning of rock slope instabilities. Earth Surf. Process. Landf. 39: 80-97. https://doi.org/10.1002/esp.3493

Accastelo, C., Blanc, S., Brun, F. (2019). A framework for the integration of Nature-Based Solutions into environmental risk management strategies. Sustainability 11: e489. https://doi.org/10.3390/su11020489

Adam, J., Augath, W., Boucher C., Bruyninx, C., Caporali, A., Gubler, E., Gurtner, W., Habrich, H., Harsson, B.J., Hornik, H., Ihde, J., Kenyeres, A., Marel, H.V.D., Seeger, H., Simek, J., Stangl, G., Torres, J.A., Weber, G. (2002). Status of the European reference frame – EUREF. IAG Symp. Ser. 125: 42–46. https://doi.org/10.1007/978-3-662-04709-5_8

Agliardi, F., Crosta, G.B., Frattini, P. (2009). Integrating rockfall risk assessment and countermeasure design by 3D modelling techniques. Nat. Hazards Earth Syst. Sci. 9: 1059-1073. https://doi.org/10.5194/nhess-9-1059-2009

Akin, M., Dinçer, I., Ok, A.O., Orhan, A., Akin, M.K., Topal, T. (2021). Assessment of the effectiveness of a rockfall ditch through 3-D probabilistic rockfall simulations and automated image processing. Eng. Geol. 283: 106001. https://doi.org/10.1016/j.enggeo.2021.106001

Alejano, L.R., Pons, B., Bastante, F.G., Alonso, E., Stockhausen, H.W. (2007). Slope geometry design as a means for controlling rockfalls in quarries. Int. J. Rock Mech. Min. Sci. 44: 903-921. https://doi.org/10.1016/j.ijrmms.2007.02.001

Andrasanu, A. (2009). Geoeducation, geoparks and geoconservation. Proc 8th European Geoparks Conference: New challenges with Geoturism, Idanha-a-Nova, Portugal, p.187.

Ansari, M.K., Ahmad, M., Singh, R., Singh, T.N. (2018). 2D and 3D rockfall hazard analysis and protection measures for Saptashrungi Gad Temple, Vani, Nashik, Maharashtra – A case study. J. Geol. Soc. India, 91: 47-56. https://doi.org/10.1007/s12594-018-0819-8

Antoniou, A.A. (2013). GIS-based evaluation of rockfall risk along routes in Greece. Environ. Earth Sci. 70: 2305-2318. https://doi.org/10.1007/s12665-013-2459-z

Asteriou, P., Tsiambaos, G. (2018). Effect of impact velocity, block mass and hardness on the coefficients of restitution for rockfall analysis. Int. J. Rock. Mech. Min. Sci. 106, 41–50. https://doi.org/10.1016/j.ijrmms.2018.04.001

Azzoni, A., La Barbera, G., Zaninetti, A. (1995). Analysis and prediction of rockfalls using a mathematical model. Int. J. Rock Mech. Min. Sci. Geomech. Bastr. 32 (7): 709-724. https://doi.org/10.1016/0148-9062(95)00018-C

Basher, L., Harrison, D., Philips, C., Marden, M. (2015). What do we need for a risk management approach to steepland plantation forests in erodible terrain. N. Z. J. For. 60, 7–10.

Baum, R.L., Godt, J.W. (2010). Early warning of rainfall-induced shallow landslides and debris flows in the USA. Landslides 7: 259-272. https://doi.org/10.1007/s10346-009-0177-0

Benjamin, J., Rosser, N.J., Brain, M.J. (2020). Emergent characteristics of rockfall inventories captures at a regional scale. Earth Surf. Process. Landf. 45 (12): 2773-2787. https://doi.org/10.1002/esp.4929

Bodin, X., Schoeneich, P., Deline, P., Ravanel, L., Magnin, F., Krysiecki, J.M., Echelard, T. (2015). Mountain permafrost and associated geomorphological processes: recent changes in the French Alps. J. Alpine. Res. 103:2. https://doi.org/10.4000/rga.2885

Bond, A., Harris, A. (2008). Decoding Eurocode 7. Taylor and Francis, London, pp. 263-304.

Bourrier, F., Berger, F., Tardig, P., Dorren, L., Hungr, O. (2012). Rockfall rebound: comparison of detailed field experiments and alternative modelling approaches. Earth Surf. Process. Landforms 37, 656–665. https://doi.org/10.1002/esp.3202

Bozdag, A. (2022). Rockfall hazard assessment in a natural and historical site: The case of ancient Kilistra settlement (Konya), Turkey. J. Mt. Sci. 19: 151-166. https://doi.org/10.1007/s11629-021-6961-6

Brandolini, P., Pepe, G., Capolongo, D., Cappadonia, C., Cevasco, A., Conoscenti, C., Marsico, A., Vergari, F., Del Monte, M. (2018). Hillslope degradation in representative Italian areas: just soil erosion risk or opportunity for development? Land Degrad. Dev. 29 (9): 3050-3068. https://doi.org/10.1002/ldr.2999

Brilha, J. (2018). Geoheritage and Geoparks. In: Reynar, E., Brilha, J. (Eds.). Geoheritage: Assessment, Protection and Management, Elsevier, Amsterdam, The Netherlands, pp. 323-335. https://doi.org/10.1016/B978-0-12-809531-7.00018-6

Briones-Bitar, J., Carrión-Mero, P., Montalván-Burbano, N., Morante-Carballo, F. (2020). Rockfall research: a bibliometric analysis and future trends. Geosci. 10 (10): 403. https://doi.org/10.3390/geosciences10100403

Bruyninx, C., Legrand, J., Fabian, A., Pottiaux, E. (2019). GNSS metadata and data validation in the EUREF Permanent Network. GPS Solut. 23: e106. https://doi.org/10.1007/s10291-019-0880-9

Cai, M., Kaiser, P.K., Uno, H., Tasaka, Y., Minami, M. (2004). Estimation of rock mass deformation modulus and strength of jointed hard rock masses using the GSI system. Int. J. Rock Mech. Min. Sci. 41: 3–19. https://doi.org/10.1016/S1365-1609(03)00025-X

Canuti, P., Margottini, C., Fanti, R., Bromhead, E.N. (2009). Cultural heritage and landslides: research for risk prevention and conservation. In: Sassa, K., Canuti, P. (eds.), Landslides- Disaster risk reduction, Springer, Berlin, Heidelberg: 401-433. https://doi.org/10.1007/978-3-540-69970-5_22

Caputo, T., Marino, E., Matano, F., Somma, R., Troise, C., De Natale, G. (2018). Terrestrial Laser Scanning (TLS) data for the analysis of coastal tuff cliff retreat: Application to Coroglio cliff, Naples, Italy. Ann. Geophys. 61 (1): 110. https://doi.org/10.4401/ag-7494

Castelle, B., Laporte-Fauret, Q., Marieu, V., Michalet, R., Rosebery, D., Bujan, S., Luban, B., Bernard, J.P., Valance, A., Dupont, P., Oul El Moctar, A., Narteau, C. (2019). Nature-based solution along high-energy eroding sandy coasts: Preliminary tests on the reinstatement of natural dynamics in reprofiled coastal dunes. Water 11: e2518. https://doi.org/10.3390/w11122518

Cecchi, C. (2015). Towards an EU research and innovation policy agenda for nature-based solutions & re-naturing cities: final report of the Horizon 2020 expert group on nature-based solutions and re-naturing cities. Directorate-generale for research and innovation, European Commission, Brussels, Belgium.

Cevasco, A., Pepe, G., Brandolini, P. (2013). Geotechnical and stratigraphic aspects of shallow landslides at Cinque Terre (Liguria, Italy). Rend. Online Soc. Geol. Ital. 24: 52-54.

Chen, G., Zheng, L., Zhang, Y., Wu, J. (2013). Numerical Simulation in Rockfall Analysis: A Close Comparison of 2-D and 3-D DDA. Rock Mech. Rock Eng. 46: 527-541. https://doi.org/10.1007/s00603-012-0360-9

Chen, T., Zhang, G., Zhang, C., Gao, X., Zheng, Y. (2019). Normal impact test of a spherical rockfall. Geotech. Geol. Eng. 37: 4889-4899. https://doi.org/10.1007/s10706-019-00949-3

Collins, B.D., Sitar, N. (2008). Processes of coastal bluff erosion in weakly lithified sands, Pacifica, California, USA. Geomorphology 97: 483-501. https://doi.org/10.1016/j.geomorph.2007.09.004

Colomina, I., Molina, P. (2014). Unmanned aerial systems for photogrammetry and remote sensing: A review. ISPRS J Photogramm Remote Sens 92: 79-97. https://doi.org/10.1016/j.isprsjprs.2014.02.013

Cooke, M.L., Simo, J.A., Underwood, C.A., Rijken, P. (2006). Mechanical stratigraphic controls on fracture patterns within carbonates and implications for groundwater flow. Sediment. Geol. 184: 225–239. https://doi.org/10.1016/j.sedgeo.2005.11.004.

Corominas, J., Mavrouli, O., Ruiz-Carulla, R. (2017). Rockfall Occurrence and Fragmentation. In: Sassa K, Mikoš M, Yin Y (Eds). Advancing Culture of Living with Landslides. WLF 2017. Springer, Cham, pp. 75-97.

Cruz, A.M., 2007. Engineering contribution to the field of emergency management, in: McEntire, D.A. (Ed.), Disciplines, Disasters and Emergency Management: The Convergence and Divergence of Concepts, Issues and Trends from the Research Literature. C. C. Thomas, Springfield, pp. 49–60.

Cuervas-Mons, J., Domínguez-Cuesta, M.J., Mateos Redondo, F., Barra, A., Monserrat, O., Valenzuela, P., Jiménez-Sánchez, M. (2021). Sentinel-1 data processing for detecting and monitoring of ground instabilities in the rocky coast of Central Asturias (N Spain). Remote Sens. 13, 3076. https://doi.org/10.3390/rs13163076

Delmonaco, G., Leoni, G., Margottini, C., Spizzichino, D. (2015). Implementation of advanced monitoring system network in the Siq of Petra (Jordan). In: G.Lollino, D. Giordan, C. Marunteanu, B. Christaras, I. Yoshinori, C. Margottini (Eds.), Engineering geology for Society and Territory 8. Springer Internation Publishing, pp. 299-303.

Domínguez-Cuesta, M.J., Ferrer-Serrano, A., Rodríguez-Rodríguez, L., López-Fernández, C., Jiménez-Sánchez, M. (2020). Análisis del retroceso de la costa cantábrica en el entorno del Cabo Peñas (Asturias, N España). Geogaceta 68: 63-66.

Domínguez-Cuesta, M.J., González-Pumariega, P., Valenzuela, P., López-Fernández, C., Rodríguez-Rodríguez, L., Ballesteros, D., Mora, M., Meléndez, M., Herrera, F., Marigil, M.A., Pando, L., Cuervas-Mons, J., Jiménez-Sánchez, M. (2022). Understanding the retreat of the Jurassic Cantabrian coast (N. Spain): Comprehensive monitoring and 4D evolution model of the Tazones Lighthouse landslide. Mar. Geol. 449 106836. https://doi.org/10.1016/j.margeo.2022.106836

Dorren, L.K.A. (2003). A review of rockfall mechanics and modelling approaches. Prog. Phys. Geogr. 27: 69-87. https://doi.org/10.1191/0309133303pp359ra

Dorren, L.K.A., Maier, B., Putters, U.S., Seijmonsbergen, A.C. (2004). Combining field and modelling techniques to assess rockfall dynamics on a protection forest hillslope in the European Alps. Geomorphology 57 (3-4): 151-167. https://doi.org/10.1016/S0169-555X(03)00100-4

Duperret, A., Genter, A., Martínez, A., Mortimore, R.N. (2004). Coastal chalk cliff instability in NW France: role of lithology, fracture pattern and rainfall. In: R.N. Mortimore; A. Duperret: Coastal chalk cliff instability. Geological Society London. Engineering Geology Special Publications 20. https://doi.org/10.1144/GSL.ENG.2004.020.01.03

Emery, K.O., Kuhn, G.C. (1982). Sea cliffs: their processes, profiles and classification. Geol. Soc. Am. Bull. 93: 644-654. https://doi.org/10.1130/0016-7606(1982)93<644:SCTPPA>2.0.CO;2

Epifanio, B., Zêzere, J.L., Neves, M. (2013). Identification of hazardous zones combining cliff retreat rates with landslide susceptibility assessment. J. Coast. Res. 165, 1681-1686. https://doi.org/10.2112/SI65-284.1

Fanos, A.M., Pradhan, B. (2016). Multi-scenario rockfall hazard assessment using LIDAR data and GIS. Geotech. Geol. Eng. 34: 1375-1393. https://doi.org/10.1007/s10706-016-0049-z

Fanos, A.M., Pradhan, B. (2019). A novel rockfall hazard assessment using laser scanning data and 3D modeling in GIS. Catena 172: 435-450. https://doi.org/10.1016/j.catena.2018.09.012

Farvacque, M., Lopez Saez, J., Corona, C., Toe, D., Bourrier, F., Eckert, N. (2019). Quantitative risk assessment in a rockfall-prone area : the case study of the Crolles municipality (Massif de la Chartreuse, French Alps). Géomorphologie 25 (1). https://doi.org/10.4000/geomorphologie.12778

Federici, B., Corradi, N., Ferrando, I., Sguerso, D., Lucarelli, A., Guida, S., Brandolini, P. (2019). Remote sensing techniques applied to geomorphological mapping of rocky coast: the case study of Gallinara Island (Western Liguria, Italy). Eur. J. Remote Sens. 52: 123-136. https://doi.org/10.1080/22797254.2019.1686957

Frodella, W., Ciampalini, A., Gigli, G., Lombardi, L., Raspini, F., Nocentini, M., Scardigli, C., Casagli, N. (2016). Synergic use of satellite and ground based remote sensing methods for monitoring the San Leo rock cliff (Northern Italy). Geomorphology 264: 80-94.

Gallach, X., Carcaillet, J., Ravanel, L., Deline, P., Ogier, C., Rossi, M., Malet, E., García-Sellés, D. (2020). Climatic and structural controls on Late-glacial and Holocene rockfall occurrence in high-elevated rock walls on the Mont Blanc massif (western Alps). Earth Surf. Process. Landf. 45 (13): 3071-3091. https://doi.org/10.1002/esp.4952

Giacomini, A., Buzzi, O., Renard, B., Giani, G.P. (2009). Experimental studies on fragmentation of rock falls on impact with rock surfaces. Int. J. Roc Mech. Min. Sci. 46 (4): 708-715. https://doi.org/10.1016/j.ijrmms.2008.09.007

Gibb, J.G. (1978). Rates of coastal erosion and accretion in New Zealand. N. Z. J. Mar. Freshwater Res. 12, 429-456.

Gigli, G., Morelli, S., Fornera, S., Casagli, N. (2014). Terrestria laser scanner and geomechanical surveys for the rapid evaluation of rock fall susceptibility scenarios. Landslides 11: 1-14. https://doi.org/10.1007/s10346-012-0374-0

Gilham, J., Barlow, J., Moore, R. (2019). Detection and analysis of mass wasting events in chalk sea cliffs using UAV photogrammetry. Eng. Gel. 250: 101-112. https://doi.org/10.1016/j.enggeo.2019.01.013

Godschalk, D.R., Beatley, T., Berke, P., Brower, D.J., Kaiser, E.J. (1999). Natural Hazard Mitigation: Recasting Disaster Policy and Planning. Island Press, Washington D.C.

Gray, J.D.E., O'Neill, K., Qiu, Z. (2017). Coastal residents' perceptions of the function of and relationship between engineered and natural infrastructure for coastal hazard mitigation. Ocean Coast. Manag. 146: 144-156. https://doi.org/10.1016/j.ocecoaman.2017.07.005

Greif, V., Sassa, K., Fukuoka, H. (2006). Failure mechanism in an extremely slow rock slide at Bitchu-Matsuyama castle site (Japan). Landslides 3:22-38. https://doi.org/10.1007/s10346-005-0013-0

Guerin, A., Stock, G.M., Radue, M.J., Jaboyedoff, M., Collins, B.D., Matasci, B., Avdievitch, N., Derron, M.H. (2020). Quantifying 40 years of rockfall activity in Yosemite Valley with historical Structure-fro-Motion photogrammetry and terrestrial laser scanning. Geomorphology 356: 107069. https://doi.org/10.1016/j.geomorph.2020.107069

Guzzetti, F., Malamud, B.D., Turcotte, D.L., Reichenbach, P. (2002). Power-law correlations of landslide areas in Central Italy. Earth Planet Sci. Lett. 195: 169-183. https://doi.org/10.1016/S0012-821X(01)00589-1

Hampton, M.A., Griggs, G.B. (2004). Formation, evolution and stability of coastal cliffs – Status and trends. U.S. Departament of the Interior, U.S. Geological Survey, Professional Paper.

Hapke, C.J., Reid, D., Richmond, B. (2009). Rates and trends of coastal change in California and the regional behaviour of the beach and cliff system. J. Coast. Res. 253. 603-615. https://doi.org/10.2112/08-1006.1

Holub, M., Hübl, J. (2008). Local protection against mountain hazards – state of the art and future needs, Nat. Hazards Earth Syst. Sci. 8, 81–99. https://doi.org/10.5194/nhess-8-81-2008

Hovius, N., Stark, C.P., Allen, P.A. (1997). Sediment flux from a mountain belt derived by landslide mapping. Geology 25: 231-234. https://doi.org/10.1130/0091-7613(1997)025<0231:SFFAMB>2.3.CO;2

Howard, E.P., Abbruzzese, J.M. (2022). A framework for assessing the performance capabilities of rock fall protections for hazard analysis and zoning. Appl. Sci. 12 (17): 8834. https://doi.org/10.3390/app12178834

Hu, B., Wu, Y., Wang, H., Tang, Y., Wang, C. (2021). Risk mitigation for rockfall hazards in steeply dipping coal seam: a case study in Xinjiang, northwestern China. Geomatics Nat. Hazards Risk 12 (1): 988-1014. https://doi.org/10.1080/19475705.2021.1909147

Hungr, O., Evans, S., Hazzard, J. (1999). Magnitude and frequency of rockfalls and rock slides along the main transportation corridors of south-western British Columbia. Can. Geotech. J. 36: 224-238. https://doi.org/10.1139/t98-106

Jaboyedoff, M., Derron, M.-H., Pedrazzini, A., Blikra, L., Crosta, G.B., Froese, C.,Hermanns, R., Oppikofer, T., Stead, D. (2012). Fast assessment of susceptibility of massive rock instabilities. In: Eberhardt, E., Froese, C., Turner, K., Leroueil, S. (Eds.), Landslides and Engineered Slopes. Protecting Society through ImprovedUnderstanding. Proceedings of the 11th International and 2nd North AmericanSymposium on Landslides (Banff, Canada, 3–8 June 2012). CRC press, pp. 459–465.

Jaboyedoff, M., Oppikofer, T., Abellán, A., Derron, M.H., Loye, A., Metzger, R., Pedrazzini, A. (2012). Use of LIDAR in landslide investigations: a review. Nat. Hazards 61: 5-28. https://doi.org/10.1007/s11069-010-9634-2

Ji, Z.M., Chen, Z.J., Niu, Q.H., Wang, T.H., Wang, T.J., Chen, T.L. (2020). A calculation model of the normal coefficient of restitution based on multi-factor interaction experiments. Landslides 18: 1531–1553. https://doi.org/10.1007/s10346-020-01556-7

Keskin, I. (2013). Evaluation of rock falls in an urban area: the case of Bogaziçi (Ercincan/Turkey). Environ. Earth Sci. 70: 1619-1628. https://doi.org/10.1007/s12665-013-2247-9

Kim, B.H., Cai, M., Kaiser, P.K., Yang, H.S. (2007). Estimation of block sizes for rock masses with non-persistent joints. Rock Mech. Rock Eng. 40, e169. https://doi.org/10.1007/s00603-006-0093-8

Kirchner, K., Kubalíková, L. (2013). Relief assessment methodology with respect to geoheritage based on example of the Deblínská vrchovina highland. In: Fialová, J., Kubíčková, H. (Eds), Public recreation and landscape protection – with man hand in hand… Conference proceeding. Brno, pp. 131–141.

Kirchner, K., Kubalíková, L. (2015). Geomythology: A useful tool for geoconservation and geotourism purposes. In: Fialová J, Pernicová D, (Eds), Public recreation and landscape protection – with man hand in hand! Conference proceeding. Brno, pp. 68–74.

Kubalíková, L., (2013). Geomorphosite assessment for geotourism purposes. Czech J. Tour. 2, 80–104. https://doi.org/10.2478/cjot-2013-0005

Kumar, P., Debele, S.E., Sanahi, J., Rawat, N., Marti-Cardona, B., Alfieri, S.M., Basu, B., Basu, A.S., Bowyer, P., Charizopoulos, N., Jaakko, J., Loupis, M., Menenti, M., Mickovski, S.B., Pfeiffer, J., Pilla, F., Pröll, J., Pulvirenti, B., Rutzinger, M., Sannigrahi, S., Spyrou, C., Tuomenvirta, H., Vojinovic, Z., Zieher, T. (2021). An overview of monitoring methods for assessing the performance of nature-based solutions against natural hazards. Earth. Sci. Rev. 217, e103603. https://doi.org/10.16/j.earscirev.2021.103603

Lacambra, C., Möller, I., Spencer, T. (2008). The need for an ecosystem-inclusive vulnerability index for coastal areas in Colombia, in: Bohle, H.-G. (Ed.), Megacities. Resilience and social vulnerability; Outcomes of the 2nd UNU EHS Summer Academy of the Munich Re Chair on Social Vulnerability, 22–28 July 2007, Hohenkammer, Germany. UNU EHS, Bonn, pp. 82–98.

Lambert, S., Bourrier, F. (2013). Design of rockfall protection embankments: A review. Eng. Geol. 154: 77-88. https://doi.org/10.1016/j.enggeo.2012.12.012

Lan, H., Martin, C.D., Lim, C. H. (2007). Rockfall analyst: a GIS extension for three-dimensional and spatially distributed rockfall hazard modeling. Comput. Geosci. 33: 262-279. https://doi.org/10.1016/j.cageo.2006.05.013

Leine, R.I., Schweizer, A., Christen, M., Glover, J., Bartelt, P., Gerber, W. (2013). Simulation of rockfall trajectories with consideration of rock shape. Multibody Syst Dyn. 32: 241-271. https://doi.org/10.1007/s11044-013-9393-4

Letortu, P., Taouki, R., Jaud, M., Costa, S., Maquaire, O., Delacourt, C. (2021). Three-dimensional (3D) reconstructions of the coastal cliff face in Normandy (France) based on oblique Pléiades imagery: assessment of Ames Stereo Pipeline® (ASP®) and MicMac® processing chains. International Journal of Remote Sensing, Taylor & Francis 42 (12), pp.4562-4582. https://doi.org/10.1080/01431161.2021.1892857

Li, M.H., Eddleman, K.E. (2002). Biotechnical engineering as an alternative to traditional engineering methods: a biotechnical streambank stabilization design approach. Landsc. Urban Plan. 60, 225–242. https://doi.org/10.1016/S0169-2046(02)00057-9.

Li, Z.H., Huang, H.W., Xue, Y.D., Yin, J. (2009). Risk assessment of rockfall hazards on highways. Georisk 3: 147-154. https://doi.org/10.1080/17499510902809763

Li, L., Lan, H. (2015). Probabilistic modeling of rockfall trajectories: a review. Bull. Eng. Geol. Environ. 74: 1163-1176. https://doi.org/10.1007/s10064-015-0718-9

Li, X., Dong, M., Jiang, D., Li, S., Shang, Y. (2020). The effect of surface roughness on normal restitution coefficient, adhesion force and friction coefficient of the particle-wall collision. Powder Technol. 362: 17–25. https://doi.org/10.1016/j.powtec.2019.11.120.

Lim, M., Rosser, N.J., Allison, R.J., Petley, D.N. (2010). Erosional processes in the hard rock coastal cliffs at Staithes, North Yorkshire. Geomorphology 114 (1-2): 12-21. https://doi.org/10.1016/j.geomorph.2009.02.011

Lorentz, J., Plassiard, J.P., Muquet, L. (2010). An innovative design process for rockfall embankments: application in the protection of a building at Val d'Isère. Proceedings of the 3rd Euro Mediterranean Symposium on Advances in Geomaterial sand Structures—AGS, Djerba, Tunisia, pp. 277-282.

Ma, K., Liu, G., Xu, N., Zhang, Z., Feng, B. (2021). Motion characteristics of rockfall by combining field experiments and 3D discontinuous deformation analysis. Int. J. Rock Mech. Min. Sci. 138: 104591. https://doi.org/10.1016/j.ijrmms.2020.104591

Margottini, C., Antidze, N. Corominas, J., Crosta, G.B., Frattini, P., Gigli, G., Giordan, D., Iwasaky, I., Lollino, G., Manconi, A., Marinos, P., Scavia, C., Sonnessa, A., Spizzichino, D., Vacheishvili, N. (2015). Landslide hazard, monitoring and conservation strategy for the safeguard of Vardzia Byzantine monastery complex, Georgia. Landslides 12: 193-204. https://doi.og/10.1007/s10346-014-0548-z

Margottini, C., Gigli, G., Ruther, H., Spizzichino, D. (2016). Advances in sustainable conservation pactices in rupestrian settlements inscribed in the UNESCO's World Heritage List. Procedia Earth Planet. Sci., 16: 52-60. https://doi.org/10.1016/j.proeps.2016.10.006

Marinos, P., Hoek, E. (2001). Estimating the geotechnical properties of heterogenenous rock masses such as flysch. Bul. Eng. Geol. Environ. 60: 85-92. https://doi.org/10.1007/s100640000090

Masuya, H., Amanuma, K., Nishikawa, Y., Tsuji, T. (2009). Basic rockfall simulation with consideration of vegetation and application to protection measure. Nat. Hazards Earth Syst. Sci. 9, 1835-1843. https://doi.org/10.5194/nhess-9-1835-2009

Matos, M. (2020). Analysis and Design of Geotechnical Structures. CRC Press, 754 p.

Mavrouli, O., Corominas, J. (2020). Evaluation of maximum rockfall dimensions based on probabilistic assessment of the penetration of the sliding planes into the slope. Rock Mech. Rock Eng. 53: 2301-2312. https://doi.org/10.1007/s00603-020-02060-z

McGinnis, R.N., Ferril, D.A., Morris, A.P., Smart, K.J., Lehrmann, D. (2017). Mechanical stratigraphic controls on natural fracture spacing and penetration. J. Struct. Geol. 95: 160–170. https://doi.org/10.1016/j.jsg.2017.01.001

Michoud, C., Derron, M.H., Horton, P., Jaboyedoff, M., Baillifard, F.J., Loye, A., Nicolet, P., Pedrazzini, A., Queyrel, A. (2012). Rockfall hazard and risk assessments along roads at a regional scale: example in Swiss Alps. Nat. Hazards Earth Syst. Sci. 12: 615-629. https://doi.org/10.5194/nhess-12-615-2012

Moore, L.J., Griggs, G.B. (2002). Long-term cliff retreat and erosion hotspots along the central shores of Monterey Bay National Marine Sanctuary. Mar. Geol. 181, 111-124. https://doi.org/10.1016/S0025-3227(01)00271-7

Moos, C., Bebi, P., Schwarz, M., Stoffel, M., Sudmeier-Rieux, K., Dorren, L. (2018). Ecosystem-based disaster risk reduction in mountains. Earth Sci. Rev. 177: 497-513. https://doi.org/10.1016/j.earscirev.2017.12.011

Morelli, G.L. (2016). Empirical assessment of the mean block volume of rock masses intersected by four joint sets. Rock Mech. Rock Eng. 49: 1759–1771. https://doi.org/10.1007/s00603-015-0882-z

Naylor, L.A., Stephenson, W.J., Trenhaile, A.S. (2010). Rock coast geomorphology: Recent advances and future research directions. Geomorphology 114, 3-11. https://doi.org/10.1016/j.geomorph.2009.02.004

O'Farrell, P.J., Anderson, P. M. L. (2010). Sustainable multifunctional landscapes: a review to implementatio. Curr. Opin. Environ. Sustain. 2: 59-65. https://doi.org/10.1016/j.cosust.2010.02.005

Okura, Y., Kitahara, H., Sammori, T., kawanami, A. (2000). The effects of rockfall volume on runout distance. Eng. Geol. 58 (2): 109-124. https://doi.org/10.1016/S0013-7952(00)00049-1

Palmstrom, A. (2005). Measurement of and correlations between block size and rock quality designation (RQD). Tunn. Undergr. Space Technol. 20: 362–377. https://doi.org/10.1016/j.tust.2005.01.005

Panizza, M. (2001). Geomorphosites: concepts, methods and example of geomorphological survey. Chin. Sci. Bull. 46: 4-5. https://doi.org/10.1007/BF03187227

Pelletier, J.D., Malamud, B.D., blodgett, T.A., Turcotte, D.L. (1997). Scale-invariance of soil moisture variability and its implications for the frequency-size distribution of landslides. Eng. Geol. 48: 254-268. https://doi.org/10.1016/s0013-7952(97)00041-0

Pfeiffer, T.J., Bowen, T.D. (1989). Computer simulation of rockfalls. Bull. Assoc. Eng. Geol. 26: 135-146.

Pham, B.T., Pradhan. B., Tien Bui, D., Prakash, I., Dholakia, M.B. (2016). A comparative study of dfferent machine learning methods for landslide susceptibility assessment : a case study of Uttarakhand area (India). Environ. Model. Softw. 84: 240-250. https://doi.org/10.1016/j.envsoft.2016.07.005

Pontee, N., Narayan, S., Beck, M.W., Hosking, A.H. (2016). Nature-based solutions: lessons from around the world. Inst. Civ. Eng. Proc. Marit. Eng. 169: 29–36. https://doi.org/10.1680/jmaen.15.00027

Pradhan, B. (2011). Use of GIS-based fuzzy logic relations and its cross application to produce landslide susceptibility maps in three test areas in Malaysia. Environ. Earth Sci. 63 (2): 329-349. https://doi.org/10.1007/s12665-010-0705-1

Prémaillon, M., Regard, V., Dewez, T.J.B., Auda, Y. (2018). GlobR2C2 (Global Recession Rates of Coastal Cliffs): a global relational database to investigate coastal rocky cliff erosion rate variations. ESurf 6, 651-668. https://doi.org/10.5194/esurf-6-651-2018

Rimbock, A., Hohne, R., Rudolf-Miklau, F., Pichler, A., Suda, J., Mazzorana, B., Papez, J. (2014). Persistence of alpine natural hazard protection. Meeting multiple demands by applying systems engine ering and life cycle management principles in natural hazard protection systems in the perimeter of the alpine convention. PLANA LP Brochure. Platform on natural hazards of the alpine convention. Vienna, Austria.

Rosser, N.J., Petley, D.N., Lim, M., Dunning, S.A., Allison, R.J. (2005). Terrestrial laser scanning for monitoring the process of hard rock coastal cliff erosion. Q. J. Eng. Geol. Hidrogeol. 38: 363-375. https://doi.org/10.1144/1470-9236/05-008

Rosser, R.N., Lim, M., Petly, D., Dunning, S., Allison, R. (2007). Patterns of precursory rockfall prior to slope failures. J. Geophys. Res. 112, F4. https://doi.org/10.1029/2006JF000642

Sala, Z., Hutchinson, D.J., Harrap, R. (2019). Simulation of fragmental rockfalls detected using terrestrial laser scans from rock slopes in south-central British Columbia, Canada. Nat. Hazards Earth Syst. Sci. 19: 2385-2404. https://doi.org/10.5194/nhess-19-2385-2019

Sarabi, S.E., Han, Q., Romme, A.G.L., De Vries, B., Wendling, L. (2019). Key enablers of and barriers to the uptake and implementation of nature-based solutions in urban settings: a review. Resources 8: e121. https://doi.org/10-3390/resources8030121

Sarro, R., Riquelme, A., García-Davalillo, J.C., Mateos, R.M., Tomás, R., Pastor, J.L., Cano, M., Herrera, G. (2018). Rockfall simulation based on UAV photogrammetry data obtained during an emergency declaration application at a cultural heritage site. Remote Sens. 10: 1923. https://doi.org/10.3390/rs10121923

Sarro, R., Pérez-Rey, I., Tomás, R., Alejano, L.R., Hernández-Gutiérrez, L.E., Mateos, R.M. (2021). Effects of wildfire on rockfall ocurrence: A review through actual cases in Spain. Appl. Sci. 11 (6): 2545. https://doi.org/10.3390/app11062545

Solheim, A., Capobianco, V., Oen, A., Kalsnes, B., Wulff-Knutsen, T., Olsen, M., Del Seppia, N., Arauzo, I., García Balaguer, E., Strout, J.M. (2021). Implementing Nature-Based Solutions in rural landscapes: barriers experiences in the PHUSICOS project. Sustainability 13: e1461. https://doi.org/10.3390/su13031461

Spadari, M., Giacomini, A., Buzzi, O., Fityus, S., Giani, G.P. (2012). In situ rockfall testing in New Soth Wales, Australia. Int. J. Rock Mech. Min. Sci. 49: 84-93. https://doi.org/10.1016/j.ijrmms.2011.11.013

Stoffel, M., Schneuwly, D.M., Bollschweiler, M. (2010). Assessing rockfall activity in mountain forest – implications for hazard assessment. In M. Stoffel; M. Bollschweiler; D.R. Butler; B. Luckman (Eds.), Tree Rings and Natural Hazards: A state of the art (Advances in Global Change Research Book 41). Springer, Dordrecht, pp: 139-155. https://doi.org/10.1007/978-90-481-8736-2_13

Sunamura, T. (1992). Geomorphology of Rocky Coasts. J*ohn Wiley and Sons*, New York, NY.

Sunamura, T. (2015). Rocky coast processes: with special reference to the recession of soft rock cliffs. Proc. Jpn. Acad. B: Phys. Biol. Sci. 91 (9): 481-500. https://doi.org/10.2183/pjab.91.481

Tang, P., Chen, F., Zhu, X., Zhou, W. (2016). Monitoring cultural heritage sites with advanced multi-temporal InSAR technique: the case study of the Summer Palace. Remote Sens 8: 432. https://doi.org/10.3390/rs8050432

Tang, J., Zhou, X., Liang, K., Lai, K., Zhou, G., Tan, J. (2021). Experimental study on the coefficient of restitution for the rotational sphere rockfall. Environ. Earth Sci. 80: e419. https://doi.org/10.1007/s12665-021-09684-6

Themistocleous, K., Danezis, C., Frattini, P., Crosta, G., Valagussa, A. (2018). Best practices for monitoring, mitigation and preservation of cultural heritage sites affected by geo-hazards: the results of the PROTHEGO project. Sixth International Conference on Remote Sensing and Geoinformation of the Environment. https://doi.org/10.1117/12.2503915

Themistocleous, K., Danezis, C. (2019). Monitoring Cultural Heritage Sites affected by geo-hazards using in situ and SAR data: the Choirokoitia case study. In: Hadjimitsis DG, Themistocleous K, Cuca B, Agapiou A, Lysandrou V, Lasaponara R, Masini N, Schereier G (eds) Remote Sensing for Archaeology and Cultural Landscapes. Springer, Cham, pp 285-308. https://doi.org/10.1007/978-3-030-10979-0_16

Touili, N., Baztan, J., Vanderlinden, J.P., Kane, I.O., Diaz-Simal, P., Pietrantoni, L. (2014). Public perception of engineering-based coastal flooding and erosion risk mitigaton options: Lessons from three European coastal settings. Coast. Eng. 87: 205-209. https://doi.org/10.1016/jcoastaleng.2014.01.004

Trenhaile, A. S. (2010). The effect of Holocene changes in relative sea level on the morphology of rocky coasts. Geomorphology 114 (1-2): 30-41. https://doi.org/10.1016/j.geomorph.2009.02.003

Turconi, L., Faccini, F., Marchese, A., Paliaga, G., Casazza, M., Vojinovic, Z., Luino, F. (2020). Implementation of Nature-Based Solutions for hydro-meteorological risk reduction in small mediterranean catchments: the case of Portofino Natural Regional Park, Italy. Sustainability 12(3): 1240. https://doi.org/10.3390/su12031240

Van der Meulen, F., Ijff, S., Van Zetten, R. (2022). Nature-based solutions for coastal adaptation management, concepts and scope, an overview. Nord. J. Bot: e03290. https://doi.org/10.1111/njb.03290

Villegas-Palacio, C., Berrouet, L., Marsiglia, S. (2020). Adaptive capacity of households to degradation of Ecosystem Services: a case stdy in the Colombian Andes. Environ. Manag. 66: 162-179. https://doi.org/10.1007/s00267-020-01305-5

Vojinovic, Z., Keerakamolchai, W., Torres, A.S., Weesakul, S., Meesuk, V., Alves, A., Babel, M.S. (2021). Towards holistic and multifunctional design of green and blue infrastructure for climate change adaptation in cultural heritage areas. In: Babel, M., Haarstrick, A., Ribbe, L., Shinde, V.R., Dichtl, D. (Eds.), Water Security in Asia - Opportunities and Challenges in the Context of Climate Change. Springer Water Series, Cham, pp. 381-390. https://doi.org/10.1007/978-3-319-54612-4-28

Volkwein, A., Schellenberg, K., Labiouse, V., Agliardi, F., Berger, F., Bourrier, F., Dorren, L.K.A., Jaboyedoff, M. (2011). Rockfall Characterisation and structural protection - A review. Nat. Hazards Earth Syst. Sci. 11. 2617-2651. https://doi.org/10.5194/nhess-11-2617-2011

Wang, X.L., Frattini, P., Crosta, G.B., Zhang, L.Q., Agliardi, F., Lari, S., Yang, Z.F., (2014). Uncertainty assessment in quantitative rockfall risk assessment. Landslides 11, 711–722. https://doi.org/10.1007/s10346-013-0447-8

Westoby, M., Lim, M., Hogg, M., Dunlop, L., Pound, M., Strzelecki, M., Woodward, J. (2020). Decoding complex erosion responses for the mitigation of coastal rockfall hazards using repeat terrestrial LiDAR. Remote Sens. 12 (16): 2620. https://doi.org/10.3390/rs12162620

Whadcoat, S.K., Rosser, N.J., Brain, M.J., Hardy, R.J. (2017). Spatial and temporal patterns of rockfalls in hard rock coastal cliffs, North Yorkshire, UK. 3rd North American Symposium on Landslides, Roanoke, Virginia, USA.

Williams, J.G., Rosser, N.J., Hardy, R.J., Brain, M.J., Afana, A.A. (2018). Optimising 4-D surface change detection: an approach for capturing rockfall magnitude-frequency. Earth Surf. Dynam. 6: 101-119. https://doi.org/10.5194/esurf-6-101-2018

Wimbledon, W.A.P., Smith-Meyer, S. (2012). Geoheritage in Europe and its conservation. ProGEO, Oslo.

Wu, M., Liu, W., Wu, R., Zhang, X. (2019). Tightly combined GPS/Galileo RTK for short and long baselines: model and performance analysis. Adv. Spac Res. 63: 2003-2020. https://doi.org/10.1016/j.asr.2018.12.008

Yepes, J., García González, C., Franesqui, M.A. (2020). Rockfall hazard mitigation on infrastructures in volcanic slopes using computer-modelled ditches. Transp. Geotech. 25: 100402. https://doi.org/10.1016/j.trgeo.2020.100402

Young, A.P. (2018). Decadal-scale coastal cliff retreat in southern and central California. Geomorphology 300: 164-175. https://doi.org/10.1016/j.geomorph.2017.10.010

Zabota, B., Kobal, M. (2020). A new methodology for mapping past rockfall events: from mobile crowdsourcing to rockfall simulation validation. Int. J. Geo-Inf. 9:514. https://doi.org/10.3390/ijgi9090514

Zhu, H.H., Shi, B., Zhang, C.C. (2017). FBG-based monitoring of Geohazards: current status and trends. Sensors 17, 452. https://doi.org/10.3390/s17030452