Environ Earth Sci (2017) 76:513
DOI 10.1007/s12665-017-6823-2

ORIGINAL ARTICLE

Beyond the boundaries of feasible engineering geological solutions: stability considerations of the spectacular Red Beach cliffs on Santorini Island, Greece

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Received: 8 March 2017 / Accepted: 8 July 2017 / Published online: 28 July 2017

Abstract The outstanding Red Beach in Santorini, a famous volcanic island in the Aegean Sea in the territory of Greece, exhibits extended rockfall instabilities along its cliffs, placing its highly frequented touristic zones at high risk. This study aimed to generate an engineering geological interpretation of these instabilities and to evaluate the degree of the rockfall potential in relation to the natural evolution of the beach. A detailed field survey of the engineering geological conditions and thorough scanning of the cliffs using terrestrial scanning (LiDAR) combined with accurate geodetic survey façade plans, enabled the detection of cinematically unstable sections. A semiautomated qualitative method for evaluating the site-specific landslide potential was also performed here using an unmanned aerial vehicle, which executed several flights around the research area 3.5 years after LiDAR scanning. The resulting products, namely a digital surface model, an orthophotograph and point clouds, were compared with the LiDAR data to evaluate the behavior of the volcanic formations at the cliff and the rockfall potential. The Red Beach cliff, mainly composed of volcanic scoria cones, was found to be very challenging case for determining a feasible engineering geological solution. Its numerous requirements with respect to rockfall control and stabilization in conjunction with the necessity of maintaining the landscape's natural beauty and preserving the adjacent archeological site further complicated the problem. However, stabilization to prevent rock falls will provoke a disruption of the balance between the sea-induced erosion and the supply of material that originates from rock falls of the natural slopes toward the beach that could put the existence of the Red Beach in significant danger. A feasible engineering geological solution for stabilizing the cliffs was investigated by evaluating all the possible protective and prevent measures. However, whether any of these measures are acceptable is doubtful.

Keywords Rockfall hazard · Terrestrial laser scanning (LiDAR) · Unmanned aerial vehicle (UAV) · Volcanic rocks · Declivity's façade · Slope stabilization

Introduction

The outstanding Red Beach on Santorini Island, Greece, is one of the most famous beaches within the Aegean and Mediterranean Seas due to its particular color, its particularly beautiful geomorphological environment, and its proximity to the remarkable archeological site of Akrotiri, which revealed a buried city after an enormous eruption during the Late Bronze (Minoan) Age. The Red Beach is located at the southeastern extent of the active volcanic island in the area known as Akrotiri (Fig. 1), which has been characterized as an archeological site.

In August 2013, a rockfall occurred in the Red Beach cliffs, and as a result, debris consisting of volcanic rocks

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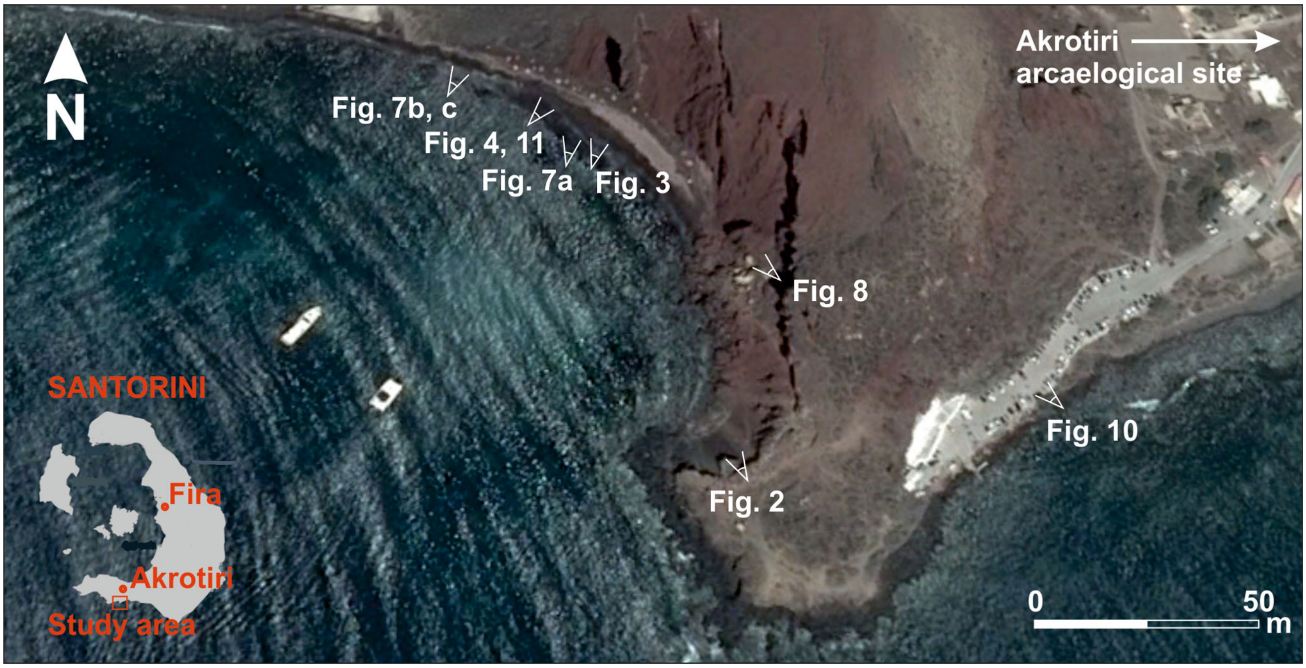

Fig. 1 Map of the Red Beach cliffs where the locations of the photographs are depicted. *source*: Google Earth

covered the whole width of the beach. Fortunately, this rockfall occurred during the night and not when the beach was crowded by tourists. However, rockfall phenomena are not limited to this recent incident. Older rock detachments are evident along the entire length of the cliff over the beach itself, and new unstable blocks have since been recognized. These rock falls are generally frequent and constitute various volumes. The hazard represented by the detachment of new blocks is significant due to the structure of the rock, the natural geomorphological evolution of the beach and the slope geometry. Almost all rockfall incidents pose an immediate danger to the beach zone and present a high risk to human safety. However, an important characteristic of the beach is that these fallen rock fragments feed the beach with material, which is how the beach has been preserved against sea-based erosion.

This study follows a common path beginning with the recognition and description of the cliffs' regional geology, engineering geological features and manifested failure mechanisms, followed by the mapping of the cliffs' surfaces and an assessment of rockfall potential in terms of frequency and magnitude, and finally, the critical consideration and evaluation of possible measures to reduce the risks of the public. At the same time, the esthetics of the environment, the requirements set by archeological restrictions and the touristic attraction of the beach posed additional boundary conditions to these problems. The aim of this paper is to present a special case for this common path that will lead to the uncommon conclusion in which a feasible engineering solution for preventing further failure, even if it is difficult and costly, must not be taken for granted. In such cases, the best engineering practice is to recognize, declare and manage the inevitable risks.

The length of the beach is approximately 300 m, while its width varies from 4 to 10 m, and it is strongly affected by sea erosion. Access to the beach is permitted via a small rocky path from a car parking area that follows a steep topography with high slopes. A view of the Red Beach cliffs and a depiction of the zonation (K1–K8) used for an assessment of the rockfall hazard are illustrated in Fig. 2.

The most recent rockfall from the volcanic formations along the beach alarmed the local municipality since it occurred within an area that was heavily crowded with tourists during a period that did not follow rainfall or an earthquake. The block was detached via toppling from the natural slope from a height of approximately 20 m, after which it broke into smaller pieces and covered the whole width of the beach (Fig. 3d). The total volume of this isolated rockfall was estimated to reach 300 m^3. The fallen mass consisted of tuff, scoria and ash clasts of different diameters ranging from 10 to 70 cm due to breakage during the fall.

Apart from this rockfall, other significant rock falls and slides have occurred in other sections of the beach. The most representative example of an older rockfall case is shown for comparison in Fig. 3a, b, where a relatively large-scale failure occurred in the central section of the Red Beach (zone K4). This instability, originating from an unknown date, consisted of an entire slope scale and involved a volume of hundreds of m^3, the fallen material of

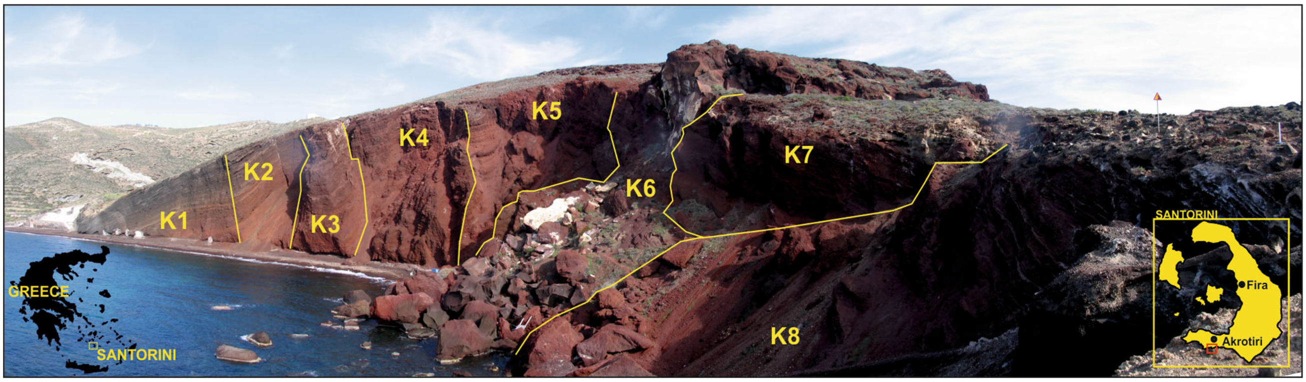

Fig. 2 Location and view of the Red Beach cliffs, where rock falls present with episodic characteristics. The zonations (*K1–K8*) used to delineate rockfall potentials are illustrated

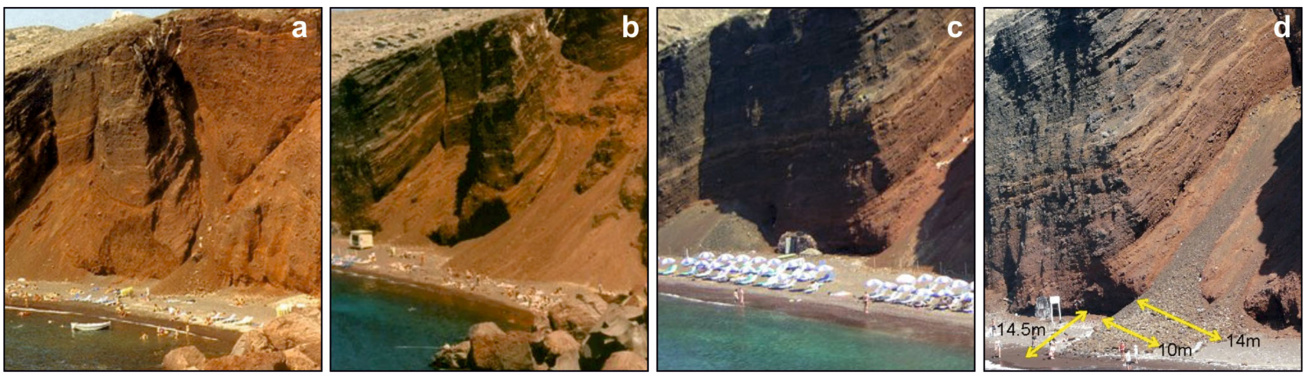

Fig. 3 Older rock falls along the Red Beach cliffs. A very large rockfall can be observed in **a** (before) and **b** (after) in the central part of the beach (zone K4, see Fig. 1). The fallen disintegrated mass covered nearly half of the beach. Other older images **c** and **d** with similar rockfall mechanisms are observed at other locations along the beach. In such cases, the material covered only part of the beach

which nearly covered the entire beach, thereby highlighting the significant hazards and associated risks within the study area. Similarly, smaller-sized blocks have been detached in zones K1 (Fig. 3c) and K2 (Fig. 3d) because the geological formation is more cemented than the formations prevalent in zones K3 and K4.

Detailed engineering geological mapping was performed, and field observations were collected to obtain the lithological characteristics, neotectonic features, structure and joint geometries, and weathering and rock strength profiles. The different engineering geological types were then discretized throughout the study area. This study was conducted in association with surveying techniques in order to identify and measure unstable rock blocks along the cliffs and determine their possible failure mechanisms. To delineate the distribution of unstable masses in detail, LiDAR and geodetic survey documentation with accurate façade diagrams were used. The episodic behavior of the rock falls and slides along the Red Beach cliffs enabled the comparison of two different point clouds in 2013 and 2017 that were acquired by LiDAR and an unmanned aerial vehicle (UAV), respectively. An assessment of the rockfall geohazards was then completed based on the rockfall frequency, cliff topography, rock mass quality and possibility of new rock falls. Nevertheless, the final and most important question is whether there is a feasible engineering geological solution that can stabilize the cliffs. All the possible measures and their applications and limitations are hereafter discussed.

Geological setting

General

The Santorini island group is the most active volcanic center of the Hellenic Volcanic Arc in the Southern Aegean Sea. Its volcanic activity started approx. 2 Ma ago, and this volcanic complex was created by several large explosive eruptions. The most recent large eruption (the Minoan or Late Bronze Age eruption, ±1630 BC) was one of the largest known volcanic explosions and created the shape of Santorini Island. Details can be found in Nomikou et al. (2012). The volcanic complex includes the islands of

Thera, Therasia, Nea Kameni, Palaia Kameni and Aspronisi, while the largest island, Thera, is semicircular, with a concave side that is open to the west.

The well-known Red Beach is a part of Cape Mavrorachidi and geologically belongs entirely to the Akrotiri Volcanic Complex (Davies et al. 1999; Sigurdsson et al. 2006). According to Friedrich (2000), the area of Akrotiri was the first instance of volcanism on Santorini Island and was formed exclusively by dacitic and andesitic volcanic products of the Pre-Minoan eruption era. Volcanic materials were produced during Akrotiri volcanic activity (650–550 ka), and cinder cones formed between 450 and 340 ka. The main characteristic of Akrotiri is the presence of these cinder cones and the chemical composition of the associated lavas, the oxidation of which produces a characteristic red color in the area (Huijsmans et al. 1988). These materials consist of fairly cemented lava fragments, stones and volcanic bombs in successive flows. Scoriae are distributed throughout the slopes of the beach, while compact lava from an old volcanic vent is found in the south side of the beach and the parking zone (Sparks and Wilson 1990).

By the end of the aforementioned volcanic phase, the Akrotiri volcanic center was reactivated (Druitt and Francaviglia 1992). The main characteristic of this activity was the creation of a "Strombolian"-type volcano as a result of the creation of cinder cone volcanoes in the areas of Cape Balos, Kokkinopetra and Mavrorachidi (Red Beach). These materials overlay lavas and tuffs from the earlier volcanic periods and are observed as superposed thin layers with a total thickness of up to 200 m, which create the slopes of the area.

The average annual precipitation for the period from 1992–1993 to 2012–2013 is estimated to be approximately 320 mm, with a minimum value of 145 mm (hydrologic year 1993–1994) and a maximum of 670 mm (hydrologic year 2002–2003).

Geological structure of Red Beach

The landscape of the Red Beach area is very steep, with volcanic slopes generally dipping up to 80° and heights reaching up to 60 m. However, sections K2 and K4 exhibit considerably less steep slopes since the rocks have failed and slid in the past, forming an angle of 35° in the lower part of the slopes and angles of 70°–80° in the upper sections. Negative dips are formed at the toe of a number of slopes due to wave erosion, which undermines the steep sections.

The aforementioned lavas consist of successive flows that can be assimilated into stratification planes. The dips of these "beds" are oriented toward the same direction as the inclination of the main slope of the beach where slides and rock falls develop.

The main joints that are measured within the volcanic masses of the area are oriented N–S to NE–SW. These measurements are identical with the primary tectonic lineaments of the Santorini volcanic center, as reported by various researchers (Mountrakis et al. 1998; Piper et al. 2004), where a recent and active extensional tectonic regime with a NNW–SSE minimum principal stress direction ($\sigma 3$) creates rupture zones along an ENE–WSW direction (Fytikas et al. 1990; Vougioukalakis et al. 1995; Mountrakis et al. 1998).

Engineering geological characteristics

It is very difficult to geotechnically characterize scoria cones or to assess their geomechanical properties due to the nature of the structure and the friable character of rocks that contain air bubbles. There are studies (del Potro and Hürlimann 2008; Apuani et al. 2005) where volcanic rocks have been classified; however, scoria cones cannot be easily quantitatively classified.

The geomaterials examined here consist of medium- to well-cemented scoria and compact lavas. In particular, the scoria is composed of alternating coarse-grained, medium-cemented volcanic breccias (5–10 cm diameter) and fine-grained (1–5 cm), well-cemented volcanic breccias (Fig. 4). When these materials fall, they lose their cohesion and disintegrate into small pieces. The two-colored rock masses of scoria (the red Sr and black Sb units, as shown in Fig. 4) are clearly separated by bedding-type surfaces consisting of angles that are lower than the dip angle of the slope face, which are consequently daylighting within the slope face, and thereby allow for the development of conditions conducive for planar sliding failure. In addition, scoria demonstrates a low tensile strength with large open tension cracks throughout the entirety of the slope.

Based on the petrography, the structure and the degree of cementation, and the structural attributes, the area is divided into five zones as shown in Fig. 5. As illustrated in Fig. 4a, the red scoria (Sr) is a medium- to well-cemented geological unit (Sr_1) (Fig. 5) consisting of the same type and size of material as the black scoria. A section located adjacent to the volcanic vent (Lv) exhibits a geological unit consisting of scoria that is well- to very well-cemented (Sr_2), the formation of which is compact and creates more distinctive blocks of rock. The black scoria (Sb) consists of highly cemented, angular lapilli-sized pyroclasts and fine-grained material, which are structured into successive flows of thin to medium thicknesses on the order of approx. 1 m. Within both geological formations, lava fragments (e.g., bombs of variable diameter and shape) may be present.

Furthermore, as already mentioned, discontinuities with N–S and NE–SW orientations are observed that are in agreement with the extensional tectonic regime of the area

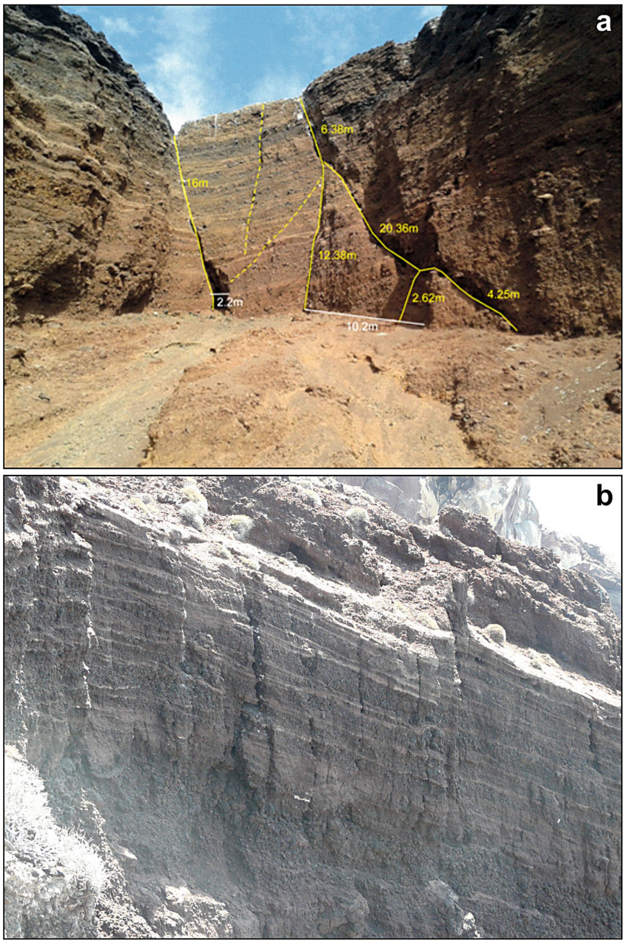

Fig. 4 Two-colored rock masses of scoria (red Sr in **a** and black Sb in **b**) that are clearly characterized by bedding-type surfaces daylighting in the slope face, which allow the possibility for the development of planar sliding failures if their strengths are low enough. Red scoria (**a**) is generally medium- to well-cemented and black scoria well to very well cemented (**b**). The friable nature of the rock along with multiple tensile cracks, which have been widened due to erosion, are evident. The toppling of rock block, due to vertical tensile and other joints, is the most frequent and episodic failure mechanism along the rock cliffs (**b**)

described by Mountrakis et al. (1998). These discontinuities facilitate the creation of new tension cracks over the face of the slope. Tension cracks with apertures of 2–20 cm have also been documented along the slope. Blocks of significant sizes have been detached following a toppling mechanism failure. Erosion along the cracks accelerated the falls (Fig. 4b). Certainly, the stability of the area is also strongly influenced by the occasional development of water pressure inside these cracks.

Andesitic-origin lava (Lv) demonstrating a high shear strength, which originated from the volcanic vent, is mapped toward the SE side of the beach above the rocky path. The mapped andesites exhibit high strength but contain open joints resulting from the cooling of the magma in addition to tensile joints and cracks in the proximity of the slopes. Finally, a large mass of numerous rockfall blocks, which originated from the andesitic vent, is located not only along the main section of the rocky path leading to the beach but also below it toward the sea.

An engineering geological conceptual model of the Red Beach cliffs is presented in Fig. 6.

Failure mechanisms

The steep inclination of the slope, the erosion induced by wave action and the low tensile strength of the scoria collectively result in the deconfinement of the rock masses and the formation of tension cracks. The toppling of rock blocks due to vertical tensile and other joints represents the main mechanism of failure along the rock cliffs (Fig. 4). Rock toppling is also the principal mechanism along the old volcanic vent, where strong rock blocks, which are separated by joints resulting from the cooling of lava and vertical stress relief joints, are overhanging.

Additionally, planar sliding of well-cemented scoria represents a secondary type of failure along the upper parts of the red cliffs since the planes of the volcanic material daylight with regard to the slope face and have low strength along the planes (Fig. 7a). Relief joints that are vertical to the lava flows favor sliding failure since smaller blocks are consequently formed, while water pressure and erosion are enhanced.

Another mechanism involves the fall of small- to medium-sized volcanic bombs that are overhanging without support due to differential erosion and wave undermining. Such bombs are present throughout the whole slope area (Fig. 7b), and thus, falling hazards are very high. These cobbles can immediately create great danger to the public, especially in zones K1 and K3, where the cliffs are almost vertical.

The slopes are substantially prone to environmentally controlled failures, which are attributed to weathering and erosional processes. As a result, the toe of the slope is slightly overhanging at a height of approximately 2–4 m, indicating that a main causing factor is erosion of the adjacent sea (Fig. 8). In addition, progressive erosion causes the raveling and release of rounded cobbles from their matrix, which then fall due to gravity. Rainfall, wind and seismic forces enhance these erosional and weathering processes.

Methodology for site mapping and rockfall potential assessment

To properly map the area of study and assess the potential of rock falls in terms of their frequency, nature and magnitude, different methods are used, as presented in the following sections.

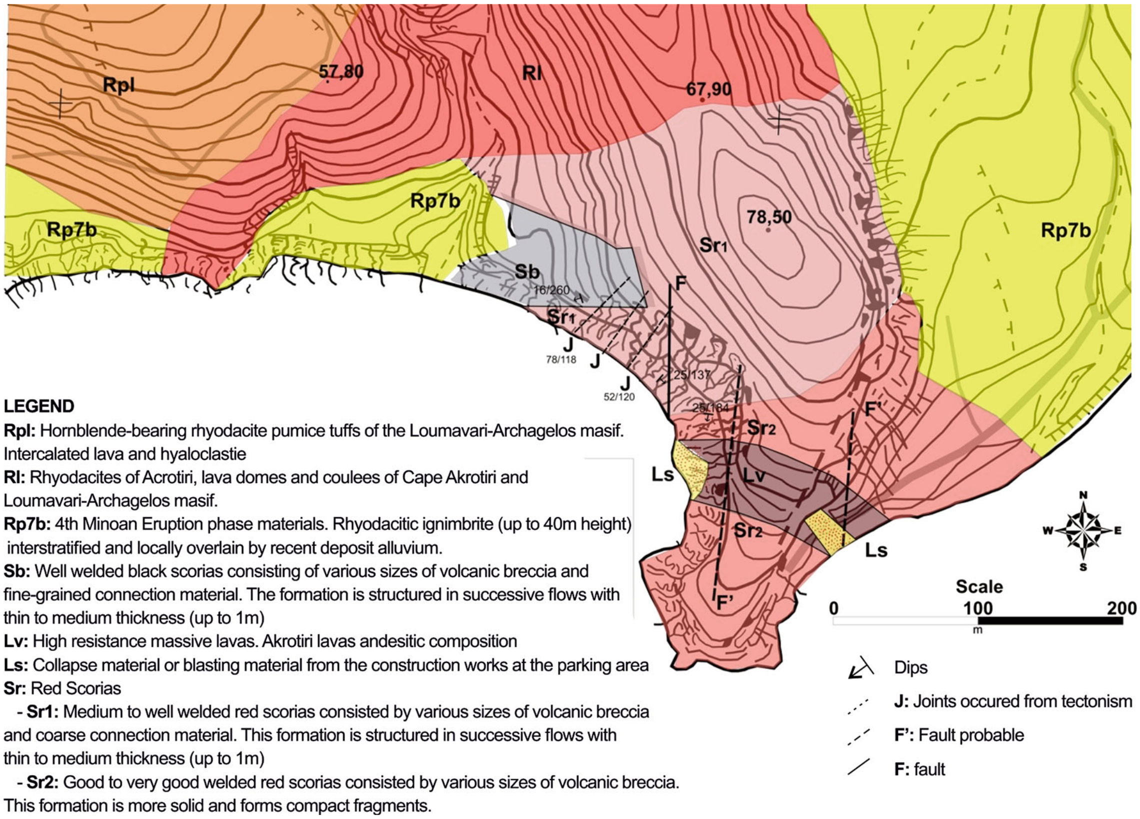

Fig. 5 Engineering geological map of the area developed for the purposes of this study. The geological formations are modified from Davies et al. (1999)

Topographic approach for unstable rock masses

A detailed topographic survey was performed in order to increase the credibility and accuracy of this study by providing a correct and accurate background in conjunction with valuable data (e.g., plans, facades and coordinates) for engineering geological zonation of the area and a rock block quantification for slope stability analysis. In particular, having compiled several vertical sections, it was feasible to locate sites that could be considered as potential sources of rock falls and to design their relevant trajectory. Having assessed these parameters, a reasonable estimate of their basic properties (e.g., the bounce height of a boulder) is possible, and thus, the design of adequate protection measures.

The magnitude of the Red Beach declivity, which is approximately 300 m in length with a maximum height of approximately 60 m, as well as the inaccessible and dangerous environment due to continuous rock falls, requires special measurement management using both classical and up-to-date surveying documentation methods. A geodetic network consisting of 5 points was established in the area of interest at specially selected, stable positions.

The field survey observations were acquired by collecting appropriate measurements of characteristic detailed points, one-by-one, which encompasses all of the rock formations within the declivity. The particularity of the case, as well as the inaccessibility of the areas defined by exceedingly steep slopes, necessitated the use of reflectorless total stations (Pantazis and Nikolitsas 2011). These instruments measure remote and inaccessible points using a laser beam. Thus, all the significant characteristics at the foot and the top of the declivity, including major cracks, large rock masses, rock crevices and peaks, rock discontinuities, undermined areas, unstable or detached rocks, and overhanging rocks, are illustrated on a façade plan (Fig. 9).

To provide complete documentation and due to the particularity of the declivity and the difficulty in distinguishing and identifying the points of interest, it was necessary to scan the declivity's façade using an image-assisted total station (IATS). The main advantage of using an IATS in comparison with a laser scanner is that an IATS produces digital models that are supported by images, which are directly referred to the established coordinate system without the need for any rectification, and thus, they are more accurate (Pantazis et al. 2013). The total accuracy of the coordinates is estimated to a few cm, which is adequate for this study, by taking into consideration the uncertainty of the points due to surface spottiness and anomalies.

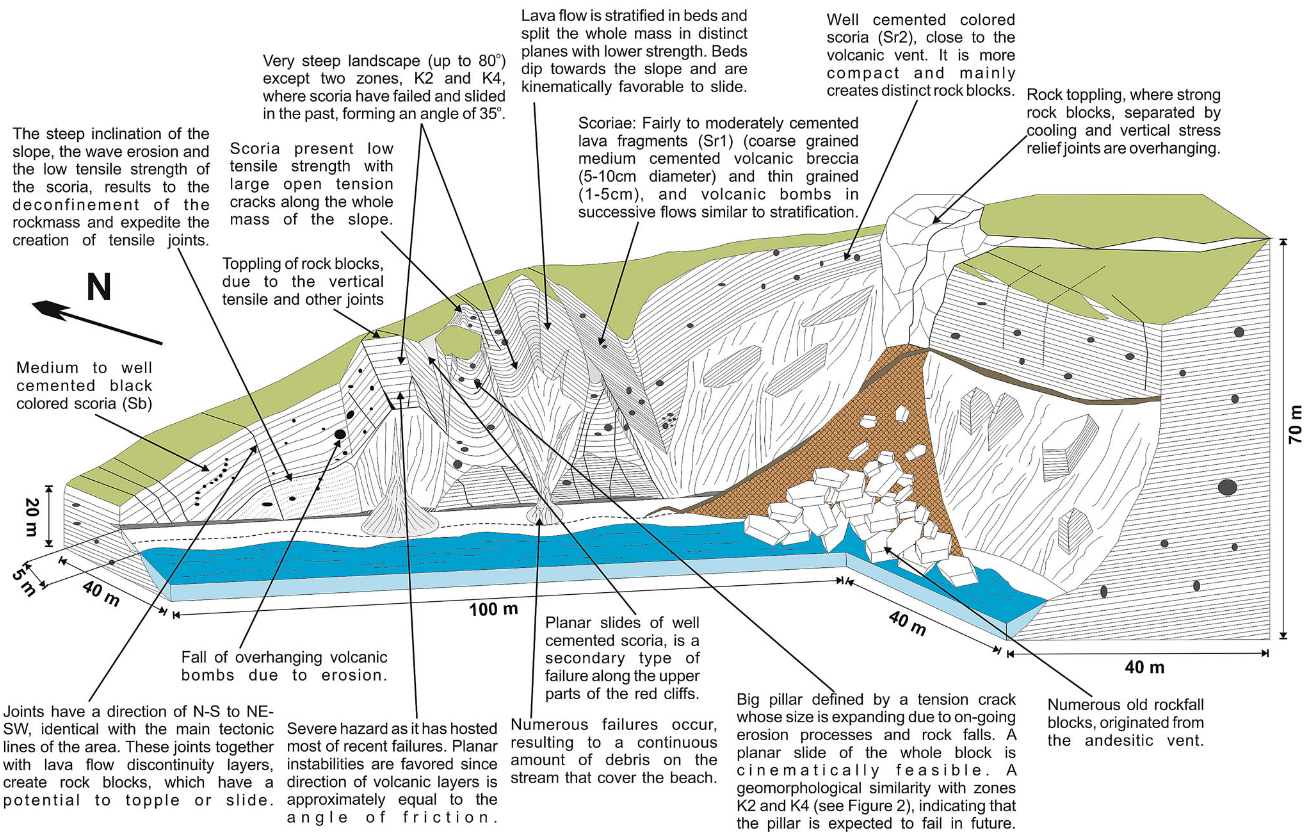

Fig. 6 Conceptual model of the geotechnical engineering conditions and rockfall phenomena along the Red Beach cliffs that was developed for the purposes of this study and is based on data provided by the results of field surveying and LiDAR scanning

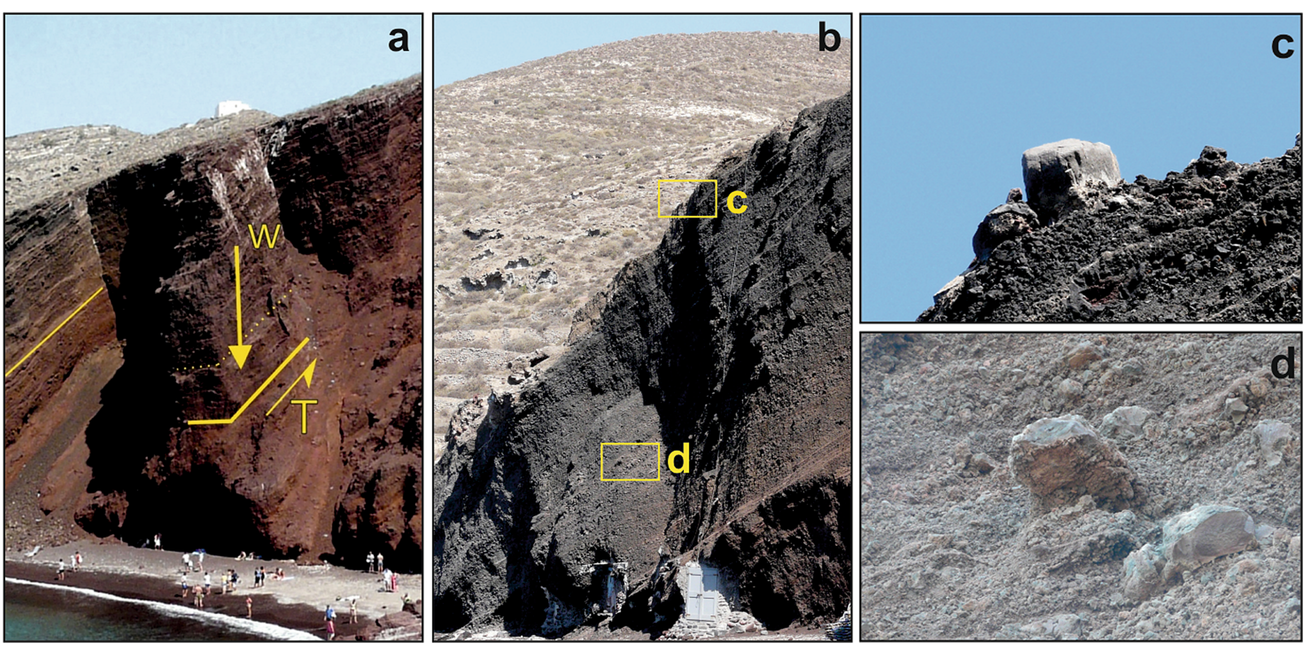

Fig. 7 Planar slides of scoria are one of the failure mechanisms since the planes of the volcanic material daylight with regard to the slope face and have low strength along the planes (**a**). The fall of volcanic bombs that are overhanging without support due to differential erosion, which poses great danger to tourists, especially in zones K1 and K3 where the cliffs are almost vertical (**b**–**d**)

Fig. 8 Slopes that are prone to environmentally controlled failure, which is attributed to erosional and weathering processes caused by wave-based erosion and the low tensile strength of scoria. This deconfinement of a rock mass leads to the formation of tension cracks and consequently, the toppling of rock blocks. These characteristics do not favor the creation of specific unstable rock blocks that can be supported. The sizes of the unstable blocks are likely to exceed 10 m, making it possible for them to overcome a rockfall barrier. As shown in the figures, there is a high rockfall hazard during the construction and positioning of rockfall barriers, and the removal of these blocks is likely to disturb the stability of adjacent side slopes

Terrestrial laser scanning (LiDAR) image processing for unstable rock masses and hazards

To collect data for the assessment of the rockfall conditions, a terrestrial laser scanning campaign was undertaken using an Optech Ilris 3D scanner.

In particular, taking into account the high and steep morphology of the slope and the relevant risks, it was evident that a detailed inventory of the dimensions of slopes that were likely to fail, as well as their trajectories, could not be acquired. Therefore, it was decided that LiDAR data should be employed in order to safely develop a precise and accurate 3D model for the identification of the main sources of rock falls and to evaluate the shape and volume of the blocks likely to fall (Fig. 10).

To obtain a high-precision outcome, the raw data (point clouds) were aligned using Polyworks software (InnovMetric) and were georeferenced using a global positioning system. Having developed the 3D model, cross sections were derived for the areas that were assessed as likely to develop rock falls based on both traditional and terrestrial laser surveys.

Unmanned aerial vehicle (UAV) image processing for unstable rock masses

Data were also collected by a low-cost UAV, which performed several flights over the research area to acquire a large number of images that were processed to generate the three post-products of aerial imagery [i.e., point cloud, orthophotograph and digital elevation model (DEM)]. One of the many advantages of the current platform is that it allows the user to easily acquire timely, very high-resolution imagery from hazardous areas, which makes it an essential tool for disaster emergency situations. The platform utilized in this study was a "built-in" platform with a digital Sony EXMOR 1/2.3″ sensor equipped with 12.4 MP and a camera lens with a 94° field of view and a 20 mm focal length. The image size was 4000 × 2250 pixels.

This study employed multi-temporal change detection techniques with two different types of datasets that were acquired with a temporal interval of 3.5 years. More specifically, the first dataset was compiled during the 2013 field operation by a terrestrial laser scanner (LiDAR). During the second field survey in 2017, UAV flights were performed to compare earth movements in the area of interest. A large number of images was collected and processed as explained previously. The primary goal was to identify and locate areas with substantial changes due to earth movements that occurred between the aforementioned dates. A binary map was initially created from a

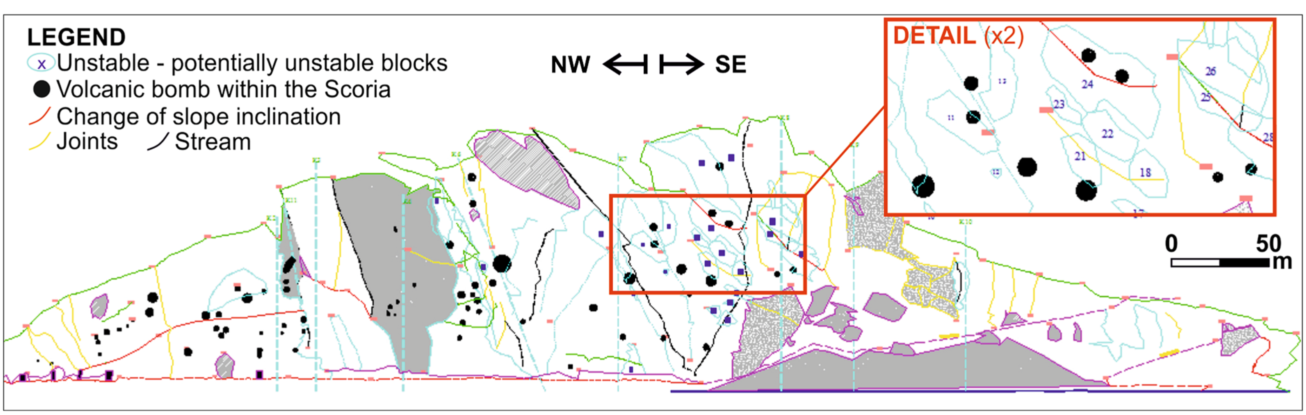

Fig. 9 Facade of the declivity of the Red Beach cliffs (please see the corresponding explanation in the text)

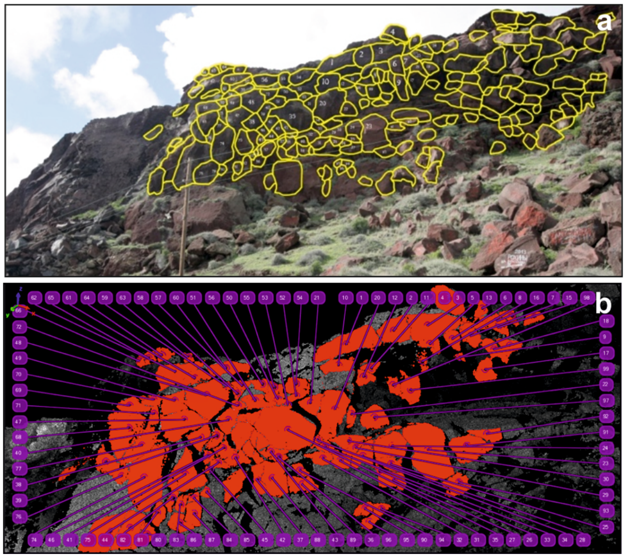

Fig. 10 Identification of volcanic rock blocks and their geometries using terrestrial laser scanning (LiDAR). Such an evaluation is clearer in the volcanic vent due to the compact-blocky nature of the geomaterial

comparison of the total area of the Red Beach. Then, a more detailed quantitative analysis was conducted on the resulting areas of interest to extract the absolute values of the differences in the earth movements. The LiDAR and UAV point clouds were first aligned manually and then automatically. In the end, statistical metrics were performed on each alignment to evaluate the results. The RMS (root-mean-square) did not exceed a value of 0.5, which indicates an accurate and precise alignment result. Some of these movements and rock falls within this timeframe can even be observed macroscopically in zone K2 (Fig. 11). However, in addition, it became obvious during the 2017 visit that a concave area existed within the slope that was later validated from a comparison between the UAV and LiDAR data. The difference in the displacement of the material during this period reached a value of 1.3 m. Other rock falls and movements were also identified by this process in zones K1 and K4 (Fig. 12).

Results: assessment of rockfall hazards

A landslide hazard was defined by Varnes (1984) as the probability of the occurrence of a potentially damaging phenomenon within a specified period and within a given area. Thus, having estimated the information regarding "when" (e.g., the temporal probability of earthquake-triggered landslide events) and the relevant information regarding "where" (e.g., the spatial probability of landslides), the landslide hazard for the study area can be evaluated by estimating the joint probability of previously investigated hazards (Jaiswal et al. 2010). Guzzetti et al. (2005) stated that the landslide magnitude or density should also be included as an additional parameter in an equation used for the estimation of landslide hazards.

The assessment of rockfall hazards and their relevant risks is usually based on published rating systems that take into account several parameters depending on the available data. The most widely accepted system is the Rockfall Hazard Rating System (RHRS) that was proposed by Pierson et al. (1990), although numerous applications of the Colorado Rockfall Hazard Rating System, which was initially developed by Andrew (1994) and later modified by Santi et al. (2009), can be found in the literature. Furthermore, Hungr et al. (2003) proposed a relevant system based on a quantitative risk assessment (QRA) procedure. More recently, Saroglou et al. (2012) developed a rockfall risk rating system involving weighted parameters (e.g., the geometry of the slope, the geological conditions and the consequences of the hazards).

In this study, the first step toward an evaluation of rockfall hazards is conducted by delineating the likelihood of a rockfall along the Red Beach area. In particular, the assessment of the potential of rock falls and slides is based on data provided both by field surveying and LiDAR scanning in order to accurately define the information regarding (i) older rock falls, (ii) rock mass quality (i.e., the type of volcanic rock, structure and cementation), (iii) height and slope angle and (iv) possibility of new rock falls.

The assessment of the rockfall potential within each distinct zone is presented along with a qualitative and relative description (Fig. 13). Considering that the beach is extremely crowded during summertime and that it hosts visitors nearly year-round, it is obvious that the relevant risk is very high.

As it has been previously mentioned, the Red Beach area consists of different volcanic formations that have been clearly identified, mapped and described. Because of this geological heterogeneity in conjunction with the region's variable topographic characteristics (e.g., slope angle), several types of slope failures have been produced. Therefore, the study area was divided into eight zones to evaluate the relevant potential per sector and to increase the credibility and accuracy of the final outcome.

In zone 1, the potential is regarded as medium to high since various failures have occurred with discrete masses of significant size. Currently, many masses are apparent along the slope where instability is visually observable, mostly toppling to be released from the NE–SW tension cracks. Additionally, plenty of cobbles are visible on the slopes surface.

Zone 2 presents very high potential, as it has hosted most of the recent failures. The slope toe is slightly

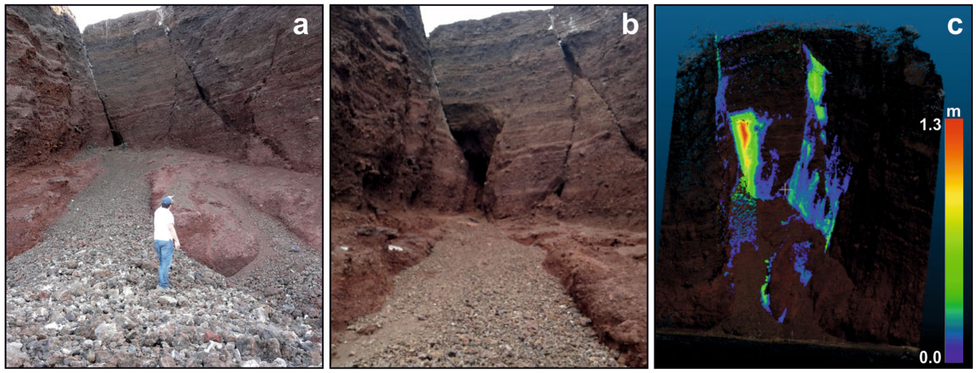

Fig. 11 A significant movement (up to 1.3 m) of scoria that occurred between two field visits in 2013 (**a**) and 2017 (**b**). A comparison between the UAV and LiDAR data validates this observation. **c** Areas in zone K2 where significant differences between rock falls and erosion along the cliff (*yellow* and *red colors*, respectively) are observed

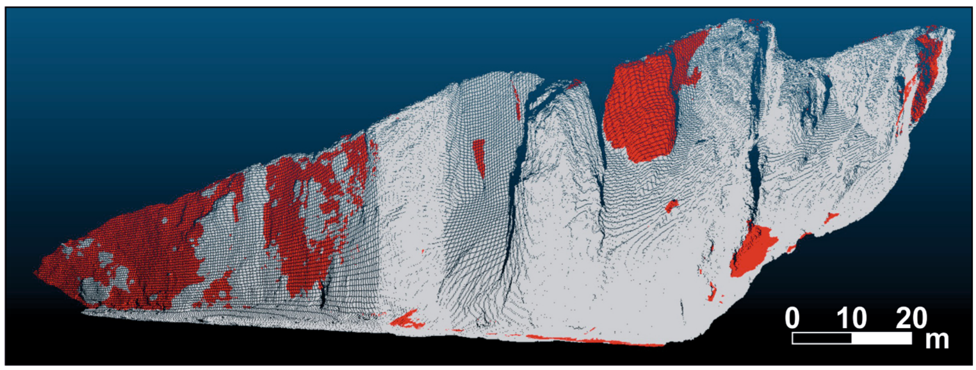

Fig. 12 An overview of the instabilities along the Red Beach cliffs between two field visits in 2013 and 2017 based on a comparison between the UAV and LiDAR data. Movements from rock falls and/or erosion are mainly identified in zones K1, K2 and K4 and are illustrated here in *red*

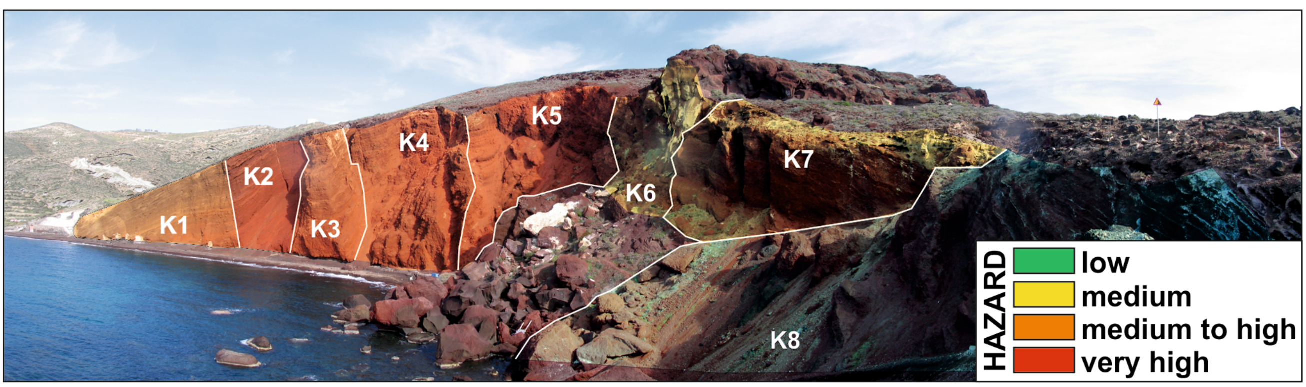

Fig. 13 Rockfall potential zoning along the Red Beach cliffs based on the history of older rock falls, the rock mass quality (i.e., volcanic rock type, structure and cementation), the height and steepness of the slope and the presence of unstable blocks

overhanging, and many cobbles are present. Plane instabilities are favored since the bedding angle is approximately equal to the angle of friction (i.e., 35°), and thus, the shear strength and dip direction of the bedding is collinear to the dip direction of the slope.

Zone 3 also presents very high potential. The slope toe is slightly overhanging, and many cobbles are present. To date, raveling has been the most common failure type, with few planar slides and toppling failures of limited size. However, the whole sector forms a large pillar (approx. 36 m in height) with almost vertical discrete surfaces. The rear surface is defined by a tension crack with a size that is expanding due to ongoing weathering and erosion processes. A planar slide of the whole block is cinematically feasible along the planes of the volcanic layers. Moreover, the zone is geomorphological similar to sectors 2 and 4, indicating that the pillar is expected to fail in future.

Zone 4 forms a cove wherein all of the materials originating from failures are concentrated within a main stream that ends a few meters above the beach level. Depending on the magnitude of the failure, its products might either temporarily accumulate and come to rest on the slope or be directly discharged onto the beach. The rock material is friable enough to cause raveling, while additional discontinuity sets favor the onset of both planar sliding and toppling. Additionally, when it transpires, surface runoff is intense due to the morphology. Therefore, numerous failures occur, resulting in a continuous amount of debris within the stream. Usually, these materials are slowly discharged, but if a failure of significant size occurs, a substantial amount of materials will rapidly spread out over the beach. Hence, the potential in zone 4 is assigned as high to very high.

Zone 5 presents medium to high potential. This zone is similar to zone 4, although the bay is significantly wider here. The slope is close to vertical and is absent any main discontinuity sets, and therefore, raveling is the most possible failure mechanism in this zone. Additionally, some cobbles are present, particularly in the middle of the slope where all loose scoria have already been detached. A major stream is apparent on the slope surface and forms the downward path of the debris. However, their flow can be easily controlled.

Zone 6 mostly affects the path leading to the Red Beach. The potential within this zone is assigned as medium. At the top, the slope is overhanging, the rock masses are dense and the joints exhibit a significant aperture, all of which permit both planar sliding and toppling. The beach is already covered by large blocks that have fallen in the past, denoting that a potential future failure will affect access to the beach. Additionally, some large blocks are scattered along the slope surface, whose motion could be triggered either by an earthquake or by heavy rain.

Zone 7 presents medium potential and consists of well-cemented scoria that form a uniform matrix. The slope is likely to have been formed after the failure of a dense rock mass, whose debris appears on the slope toe, since a failure surface is present. Only the toppling of few small blocks from the crest is feasible, but since the slopes above the path are relatively gentle and shallow, the likelihood of such a failure is minor.

Zone 8 presents low potential. The slope is steep near the crest where some relatively small blocks can slide or topple. However, the toe consists of loose scoria, which can act as a buffer and allow the blocks to come to rest.

Discussion: mitigation steps and non-feasibility

Available stabilizing and protective measures

The mitigation of risk can be assessed based on two general strategies: hazard or/and consequence/risk reduction. Hazard reduction is comprised mainly of the stabilization of potential failures, thereby reducing the likelihood of a failure to initiate. On the other hand, risk reduction can be achieved by controlling the effects of a failure, i.e., eliminating negative consequences. In any case, mitigation measures must satisfy some basic criteria along with site-specific particularities.

The Red Beach belongs within the broader archeological site of Akrotiri, which was founded by the Minoan civilization roughly in the span between the twentieth and the seventeenth centuries BC. In such sites, intervention measures must be minimal and are strictly controlled by the National Archaeological Board of Greece. Additionally, the generation and sole retention mechanisms of the beach are attributed to frequent failures of the natural slopes. Continuous feeding of the beach level with debris material balances the erosive processes of the sea and maintains the width of the beach. Obviously, the prevention or significant impairment of debris materials falling to the base of the slope would result in the disappearance of the beach within a limited time span.

The effectiveness, constructability, durability, cost, maintenance and esthetics of the mitigation measures pose additional design criteria for potential remedial measures. Effectiveness is a function of the geometric and geotechnical properties of the slope as well as the failure mechanisms, which differ among the Red Beach slopes. Therefore, more than one type of remedial measure must be implemented, which will result in increased complexity.

The constructability of the beach is crucial since a proper installation ensures the successful operation. However, construction techniques are significantly limited due to the difficult access to the beach. No roads lead to the beach, and they cannot be created since they will either pass through the archeological site or require extensively cut slopes. In addition, the slopes are high (up to 60 m tall), and the beach is narrow (in some locations, it is less than 5 m wide). Therefore, it is difficult to plan site construction operations without site intervention, which will not be accepted due to archeological restrictions. Moreover, safety during construction is also an issue since the metastable cobbles might detach at any time, especially from the vibrations caused by machinery.

Durability is important because a corrosive environment will severely reduce a measure's service life. Additionally, any implemented mitigation measure must be able to cope with any differentiation to the morphology that will appear during its life span. However, the processes that affect the slopes modify the morphology to some extent on an annual basis.

The esthetics of any engineered measure must not be obtrusive on any occasion, especially since the popularity of the beach is attributed to its natural morphology.

Feasibility evaluation: applicability of hazard reduction techniques

Since the main factors that cause slope failures are the extended height and the steep inclination of the slope, resloping is the first consideration. Cutting the slope at shallower angles and introducing berms will result in an increase in the slope stability safety factor and will limit the spatial extent of tension cracks since the stresses will be more effectively distributed, facilitate more easily controlled water runoff and allow for the installation of additional measures in the slope (i.e., barriers). However, this solution poses a serious disturbance to the landscape. As can be evidenced by stability analyses, ensuring the desired levels of risk by reducing the associated hazards requires an extensive change of the geometries of the slopes. Moreover, since failures will be eliminated, the feeding and erosion cycle of the beach will be disrupted, and the beach will gradually vanish.

Scaling is necessary in order to address the cobbles found on the slope surface and on some discrete unstable blocks, thereby limiting hazards to some extent but not to an acceptable level. Scaling is a temporary measure that must be repeated on an annual basis due to the erosive environment. However, scaling must be performed before any other form of intervention in order to create safe working conditions.

Reinforcement dowels and rock bolts combined with cable lashing or wire meshes can be implemented to increase shear strength and stabilize precarious blocks. However, the weak structure of the rock masses along with the numerous discontinuities sets makes it difficult to identify the unstable blocks and necessitates a dense bolt pattern of significant length. However, such an approach is problematic since access to the beach is limited, the associated cost is significant, and the durability is questionable due to the excessively erosive environment. Additionally, the beach landscape will be moderately downgraded. It is likely that the placement of spot dowels and rock bolts absent wire meshes and cables (i.e., a limited esthetic disturbance) will be ineffective due to the friable nature of the unstable blocks (representing a limited potential for the distribution of anchor forces), and the dynamic evolution of erosive forces will quickly render any rational bolt pattern insufficient.

Rockfall and debris barriers can be implemented to reduce the risks, as they limit the consequences of a failure. However, these barriers cannot be installed at the beach level since they would occupy its full width, as the beach is narrow (Fig. 8). Consequently, the barriers must be installed on the slope surface, which is also problematic. Except for zones K2 and K4, the slopes possess significant height and are either overhanging or vertical, and thus, any barrier must be horizontally installed at least 10 m above sea level in order to have the necessary free space to elongate. Additionally, the required width would be slightly shorter than the width of the beach, which represents a significant esthetic downgrade. In zones K2 and K4, the barriers can be installed on the edge of the vertical slope at a height of approximately 10 m above the beach level. However, the main problem is their maintenance, which must be frequent.

The applicability of these hazard reduction techniques and their limitations are summarized in Table 1.

Admitting the boundaries: lessons learned

This research project was conducted to perform a semi-automated qualitative analysis with which to evaluate site-specific rockfall hazards in the famous Red Beach cliffs on the island of Santorini. The major goal of this study was to provide feasible engineering geological solutions to stabilize the slopes along the beach while respecting the need to retain the landscape and the esthetics of the beach, which is a major tourist attraction, and simultaneously heeding the archeological restrictions.

The rock slope stability of the Red Beach cliffs, which consist of scoria cones, is mainly dictated by the moderately cemented rock, the dip direction of the lava flows, the vertical joints along the steep slope (i.e., due to the stress relief of the rock surfaces), and the erosional effects of the sea.

A detailed field survey of the engineering geological conditions, as well as thorough scanning of the cliffs conducted using LiDAR and a UAV, combined with accurate geodetic survey profiles, enabled the detection of kinematically unstable sections. This study used two different types of datasets, which are composed of LiDAR data acquired in 2013 and a UAV flight performed in 2017, to compare earth movements in the area of interest. Indeed, the movement and fall of volcanic rocks along several sections of the Red Beach cliffs were identified through this comparison and considerations of the macroscopic observations. The frequent repeatability of rock falls and slides throughout the cliffs, the poor to moderate quality of the rock, and the high, steep slopes in conjunction with the natural evolution of the slopes due to sea-based erosion raise the potential degree and the relevant hazard for new rock falls to high levels.

Based on the best international practices and relevant guidelines, the effective reduction of rockfall risks with acceptable levels of long-term maintenance throughout the Red Beach cliffs (i.e., if one could forget its esthetic and archeological uniqueness) would demand extensive, extremely difficult and diligent stabilization and protective measures concordant with a very high financial burden. Based on clear geotechnical criteria, these measures would most likely also include decisive intervention with regard to the geometry of the natural slopes above the beach, which would dramatically affect the esthetics of the beach.

Table 1 Possible support measures along the Red Beach cliff: applications and limitations

Measures	Remarks
Slope angle reduction	Dramatic interfering to the scenery of the beach
	Interference to the deposition–erosion cycle of the beach
Bolting—wire net	Friable nature of the scoria, reduced effectiveness
	Dynamic evolution of the phenomena, difficult to predict the unstable masses (newly blocks created)
	Uncertainty of the necessary length
	Difficult access
Net of spider type	Only locally to some rock blocks (old crater)
	Inappropriate surrounding environment for adequate anchoring
Scaling of rock blocks	Temporary measures due to the dynamic evolution of the phenomena
	Difficult access to many parts of the slope
	Danger of greater block detachment during the scaling works
Barriers for rock falls and debris flow	Application in the middle of the slope:
	High hazard during the construction works, disruption of the slope equilibrium
	Great scale and friable nature of the rocks, danger to overpass the barriers
	Difficult to maintain—removal of debris
	Dramatic degradation of the esthetic
	Application to the beach level:
	Beach embargo, almost for the whole length
Exclusion of the beach use—distant use of its view	Ensure the reasonable risk
	Zero «construction» cost
	Zero effect to the environment

Meanwhile, the disruption of the balance between the erosion caused by the sea, as well as supply of materials that originate from the falls of the natural slopes toward the beach, could put the existence of the beach in significant danger. Even if costs were not an issue and a well-organized maintenance campaign was applied toward the periodic recharge of the beach using the controlled deposition of material from gentle, safe cliffs to ensure its existence, the character and uniqueness of the Red Beach would be forever lost. Therefore, the Red Beach in Santorini is an excellent example of a case wherein the engineering geologist and the geotechnical engineer should admit that the boundaries of possible solutions have been met and must not be crossed regardless of any financial factor. The only way to reduce risk to acceptable levels without destroying this unique natural feature is to minimize the exposure of the public to the beach so that everyone can safely admire it.

Acknowledgments We thank the Municipality of Thera for funding this research.

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