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ORIGINAL ARTICLE

Evaluation of rock slope stability for a touristic coastal area near Kusadasi, Aydin (Turkey)

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Abstract The study area, which will be open to tourism in Kusadasi (Aydin), has steep and high cliffs on the Aegean coast in Turkey. Flysch is the main lithological unit and consists of alternating sandstone–claystone–marl sequences. Some sliding and rockfall problems have occurred in the area in the past, so potential geological hazards need to be investigated to ensure the safety of tourists. The aim of this study is to mitigate geological hazards by recommending engineering solutions, which will ensure the continuation of the nature-friendly appearance of the slopes. To accomplish these tasks, a geological survey was performed. It involved gathering information on rock discontinuities by means of scan-line surveys and collection of rock samples. Furthermore, in situ and laboratory tests were also carried out. The data collected from the field and laboratory test results were used to perform slope stability and rockfall (2-D and 3-D) analyses for different slope conditions along 43 profiles. Based on the analyses, rockfall was found to be the main slope instability problem in the study area. Under the light of these studies, rock removal, drainage, greening (vegetation), filling of caverns, protective wall building and erosion prevention are offered as remedial measures.

Keywords Flysch · Rockfall · Slope Stability · Kusadasi · Turkey

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Introduction

Kusadasi is a touristic coastal town in the Aydin province of Turkey. A coastal area located about 5 km south of Kusadasi is now under rehabilitation and will be open for tourism in the next few years. However, this area is seriously affected by landslide and rockfall problems where steep and high cliffs (Fig. 1) near the coast pose a great danger to future tourists. Some sliding and rockfall problems have already been observed in the past. These geological hazards need to be investigated and remedial measures which keep the nature-friendly appearance of the slopes should be taken in preparing the area for touristic use. The study area covers 0.24 km^2 and has a flat morphology in general but it has steep cliffs on the coast especially at the western part of the region (Fig. 1). Access to the study area is from the Kusadasi-Söke highway in all seasons.

A number of studies related to sliding and rockfall problems exist in the literature (Pfeiffer and Bowen 1989; Turner and Schuster 1996; Guzzetti et al. 2002; Crosta and Agliardi 2003; Schweigl et al. 2003; Wyllie and Mah 2004; Dorren et al. 2004, 2005; Frattini et al. 2008; Choi et al. 2009; Paronuzzi 2009; Tunusluoglu and Zorlu 2009; Binal and Ercanoglu 2010; Volkwein et al. 2011; Ramírez-Herrera et al. 2012; Tanarro and Munoz 2012; Alejano et al. 2013; Fityus et al. 2013; Singh et al. 2013; Shi et al. 2013; Youssef et al. 2015).

The aim of this study is to mitigate geological hazards by suggesting remedial measures which maintain the nature-friendly appearances of the slopes. Slope stability and rockfall (2-D and 3-D) analyses were carried out to design mitigation measures. In this study, methodologies adopted by Kentli and Topal (2004), Öztekin et al. (2006), and Topal et al. (2007, 2012) are considered. They mainly

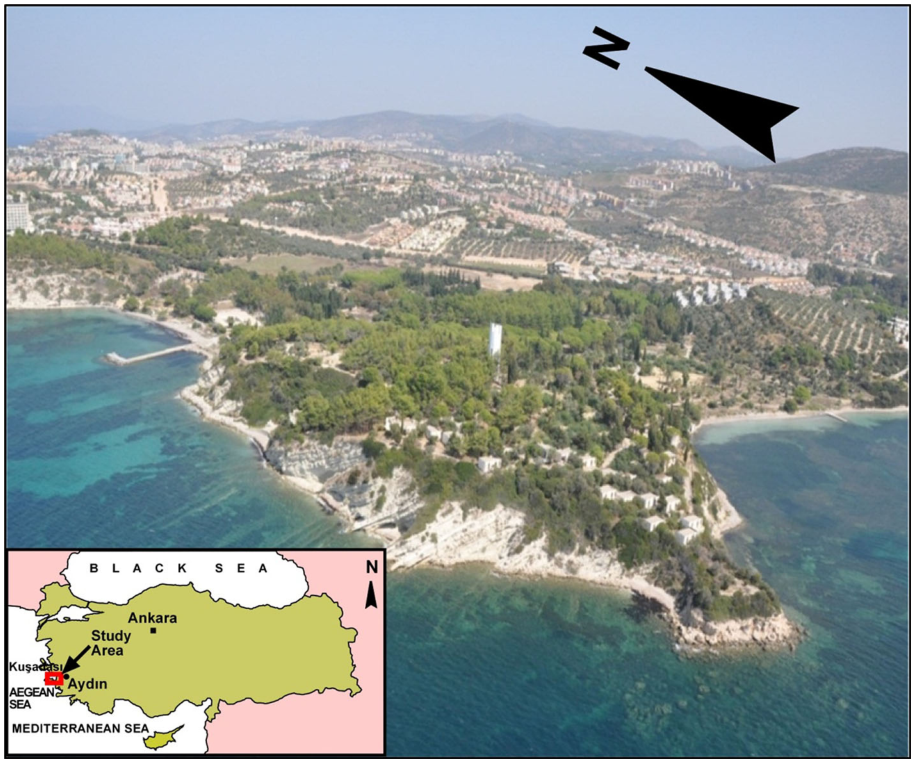


Fig. 1 General view of the study area with the steep cliffs near the coast

include field and laboratory studies, followed by stability analyses and field checking of the findings.

A typical Mediterranean climate is dominant in the study area. It is hot and dry in summers but mild and rainy in winters. According to meteorological data (DMI 2012), the highest temperature observed in the region is 44.6 °C in July and the lowest temperature is −6.0 °C in January. The annual amount of precipitation is 618.0 kg/m^2. The study area is a green field compared to its immediate surroundings. The area has scrub-type vegetation. Additionally, there are different tree species like black pine, stone pine, olive, eucalyptus, phoenix, palm, calabrian pine, black cypress, pepper and locust.

Methods and materials

To assess the slope instability problems and take possible mitigation measures, the investigation started by gathering available documents, maps, and other geological studies of the area. Then, detailed scan-line surveys all around the coast were performed. During this study, Schmidt rebound measurements were also carried out with an L-type hammer according to ISRM (1981) from different levels of rocks outcropping in the field. Many block samples were taken for the laboratory tests including unit weight, effective porosity, water absorption, point load strength and direct shear tests along the rock discontinuity surfaces. Geological hazards like slides and rockfalls were investigated in detail. Because the literature gives different values for the coefficient of restitution, which is one of the most important parameters used in rockfall analyses, in situ rockfall tests were carried out by throwing a total of 66 rock blocks along 2 different routes. Kinematic, slope stability and rockfall (2-D and 3-D) analyses for 43 profiles were then carried out for three different slope configurations with the original slope, an inclined slope and a benched slope. The accuracy of the model was further verified by comparing the results derived from the 2-D and 3-D rockfall analyses. Finally, considering all the collected data, remedial measures that would incorporate the nature-friendly appearances of the slopes were suggested as ways to solve the geological problems.

Geology

The study area is located in the western part of the Büyük Menderes Graben. The Menderes Massif metamorphics comprise the basement of the study area (Yılmazer et al. 1994). Various geological units crop out in this region (Fig. 2). These are schist (upper Paleozoic), marble (middle Triassic–Cretaceous), meta-flysch (upper Cretaceous) and continental carbonates including flysch material (middle–upper Miocene) from older to younger. However, the main unit present in the study area is the flysch material. It is gray, light brown, thin to thick bedded, and moderately weathered. It contains alternation of weak

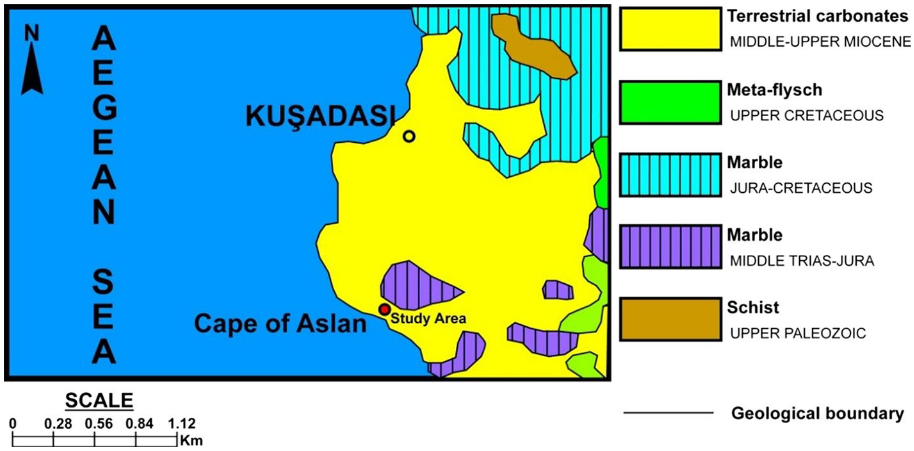


Fig. 2 The geological map of the study area and its close vicinity (simplified from MTA 2002)

sandstone–claystone–marl. The study area is located in the first-degree seismic zone of Turkey where there is a 90 % probability of expected peak horizontal ground acceleration values that exceed 0.4*g* occurring within 50 years, according to the Earthquake Zoning Map of Turkey (GDDA 1996).

Field and laboratory studies

Data collection was performed by means of field and laboratory studies. In the field, soil and rocks were investigated in terms of their engineering geological properties. Data on discontinuities were collected according to Priest (1993) by means of a scan-line survey along 10 profiles. Schmidt rebound hardness measurements were taken from various locations and field rockfall tests with 66 block samples were performed along two different profiles to assess the coefficient of restitution. Samples were also collected for laboratory studies (Fig. 3).

The rocks in the study area are generally gray, light brown, thin to thick bedded and moderately weathered. They consist of an alternation of sandstone–claystone–marl. The most common discontinuity is the bedding plane. Additionally, joints have developed, mainly in two different orientations (Fig. 4). The changes observed in the major discontinuity sets are related to the deformation of the layers.

The thickness of the layers (beds) ranges from 1 to 50 cm. The layers are continuous and their surfaces are generally rough. The kinematic analyses carried out according to Wyllie and Mah (2004) reveal that except in the second, fourth, and fifth locations, no failure is expected in the study area. In the second location (Fig. 5), sliding-type (plane failure) movements and erosion could be seen, while in the fourth and fifth locations wedge failure is expected. Because the dimension of the blocks causing the wedge failure is very small, the failure is expected to be manifest in rockfall mode (Fig. 6). A typical

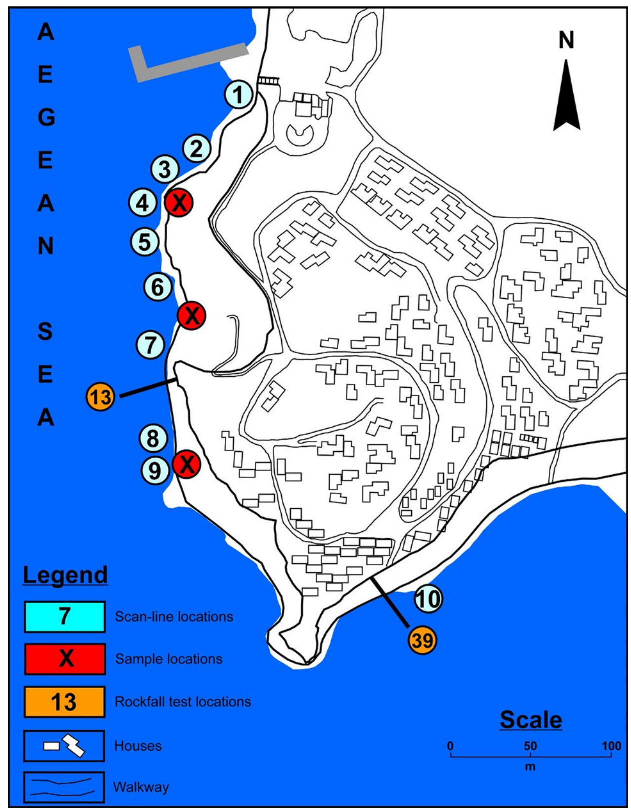


Fig. 3 The scan-line, sample and rockfall test locations in the study area

kinematic analysis for the 4th location is presented in Fig. 7. Groundwater is not encountered in the area. Oxidation marks on the joint surfaces can be seen occasionally in the field. The average Schmidt rebound value of the unit is found to be 42.

In the laboratory, unit weight, effective porosity, water absorption and point load strength tests were performed on ten samples taken from the field according to ISRM (1981) and ISRM (1985). According to the tests performed on the samples (Table 1), the dry and saturated unit weights are

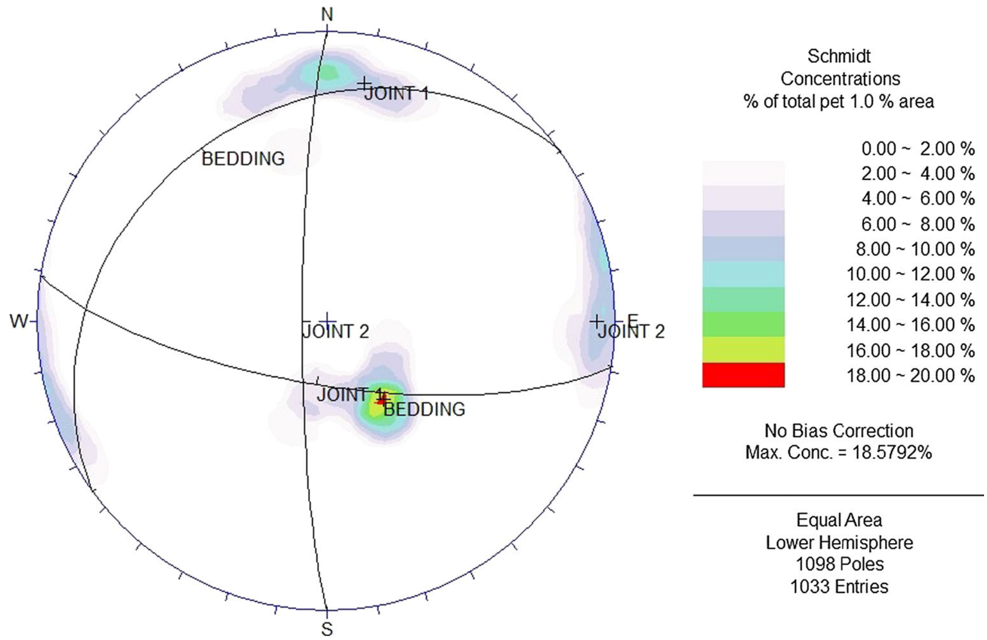


Fig. 4 Stereographic projection of the major discontinuity sets in the study area

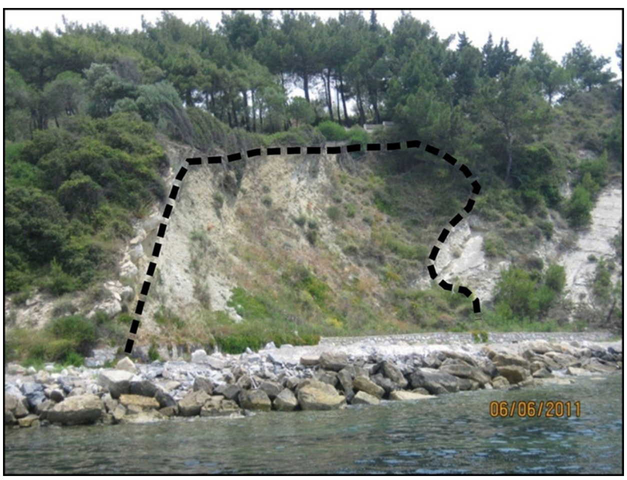


Fig. 5 Very weak sandy siltstone unit

Fig. 6 Photograph showing fallen rocks at the coast

23.60 and 24.48 kN/m^3, respectively. Effective porosity and water absorption values are 9.01 and 3.89 %, respectively. The average point load strength index (Is_{50}) value is found to be 6.06 MPa. The sampling could not be performed in the claystone because it is very weak. The flysch material tested has a moderate unit weight and porosity according to Anon (1979).

Slope stability and rockfall analyses

Rock mass stability analyses

Circular rock mass failure analyses were carried out along 43 profiles due to the weak and highly jointed nature of the rocks at the coast. The required rock mass shear strength parameters for the limit equilibrium analyses were obtained for these 43 profiles (Fig. 8) by using RocLab 1 software (Rocscience 2011). Because of the blocky structure and very poor surface conditions of the area, the geological strength index (GSI) value (Hoek 2007) was defined as 33. The uniaxial compressive strength value was obtained by

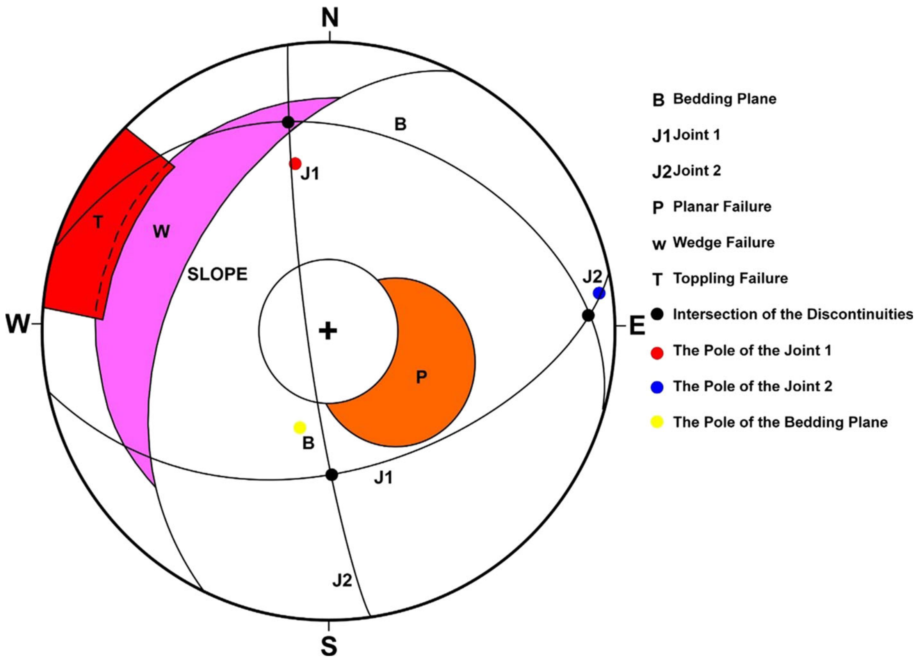


Fig. 7 A typical kinematic analysis for the 4th profile

Table 1 Laboratory results of the samples taken from the field

Tests performed	Number of samples	Average value
Unit weight-dry (kN/m^3)	10	23.60
Unit weight-saturated (kN/m^3)	10	24.48
Point load strength (MPa)	10	6.06
Effective porosity (%)	10	9.01
Water absorption by weight (%)	10	3.89

correlating the average Schmidt hammer hardness and unit weight values. A uniaxial compressive strength of (σ) = 35 MPa, an intact rock parameter of (mi) = 5 and a disturbance factor of (D) = 0.7 were used as input values recommended by Hoek (2007). The rock mass shear strength parameters (c and ϕ) were assessed by considering the height of every profile.

The shear strength values obtained for highly jointed rock mass were used in slide 5.1 software (Rocscience 2004a). Limit equilibrium analyses were performed separately for three different conditions at every profile (original slope, inclined slope and inclined with one-bench slope). The rock mass was divided into 30 slices and analyzed using the simplified Bishop method (Bishop 1955). A maximum horizontal ground acceleration value of 0.15g was considered for the pseudostatic analysis because the study is located in the first-degree earthquake zone of Turkey. Since groundwater was not encountered in the area, the analyses were performed in dry conditions. However, the saturated unit weight value was used to represent the conditions after a rainy period. A typical

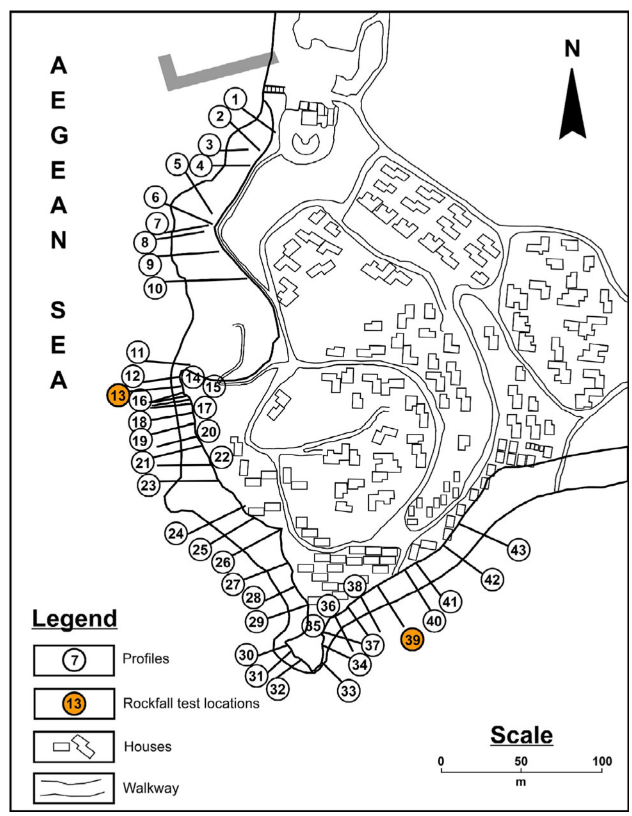


Fig. 8 The profiles where rock mass failure and rockfall analyses are performed

example of limit equilibrium analysis for the 39th profile of the original slope is given in Fig. 9. The factors of safety (Abramson et al. 2002; Duncan et al. 2014) values for all

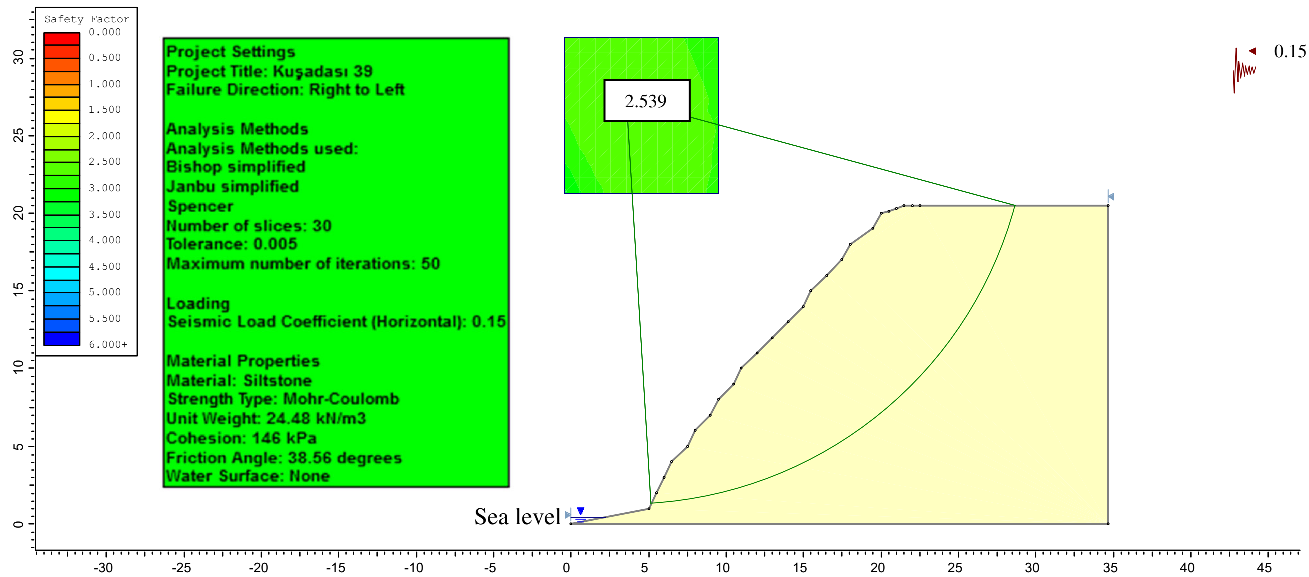


Fig. 9 The result of limit equilibrium analysis for the 39th profile of the original slope

slope types are much higher than 1.5 for all three slope conditions, and circular mass failures are therefore not expected in the cliffs of the study area.

Rockfall analyses

Rockfall can be described as the rapid movement down a slope of one or a few boulders (Varnes 1978). The rockfall may be formed because of jointing, weathering, freeze–thaw, the effects of water, earthquakes, or tree roots (Chen et al. 1994; Wasowski and Gaudio 2000; Marzorati et al. 2002; Dorren 2003; Topal et al. 2007; Krautblatter and Moser 2009; Tunusluoglu and Zorlu 2009; Wick et al. 2010; Binal and Ercanoglu 2010). Rockfall threatens humans and can cause significant damage to structures (Topal et al. 2012). For land use planning in rockfall-prone areas, the causes of rockfall events and remedial measures should be considered (Raetzo et al. 2002; Agliardi and Crosta 2003; Corominas et al. 2005; Jaboyedoff et al. 2005; Straub and Schubert 2008; Fell et al. 2008; Agliardi et al. 2009; Wang et al. 2014). The dynamic processes of a rockfall event may be free-fall, bouncing or rolling, depending on the geometrical features and mechanical properties (friction, roughness, rolling resistance, restitution characteristics, etc.) of the slope and rock blocks (Ritchie 1963; Agliardi and Crosta 2003; Alejano et al. 2010; Ansari et al. 2014). As the profile changes, two or more of the rockfall modes may also be observed, depending on the different dynamic processes. Additionally, initial velocity, weight and shape as well as the fragmentation of the blocks and the properties of the slope-forming material may control the rockfall event (Giani 1992; Azzoni et al. 1995; Dorren 2003).

In this study, both 2-D and 3-D rockfall analyses were carried out following the procedures described by Turner and Schuster (2012) and Wyllie (2015). To perform the 2-D rockfall analyses, the dimensions of the blocks prone to fall were defined by analyzing the dimensions and positions of the fallen blocks and using the scan-line survey data performed at ten locations in the field. 66 rock representative blocks were made to fall along profiles 13 and 39 (Fig. 8) to define the normal and tangential coefficient of restitutions (R_n and R_t) quantifying velocity changes during impact (Wyllie 2015). RocFall 4.0 software was used for the 2-D rockfall analyses. It is a rockfall simulation program with lump mass formulation for the prediction of rockfall behavior on slopes and the design of rockfall barriers. First, slope profile is created. Then, material properties such as normal and tangential coefficient of restitution, friction angle, slope roughness are defined. After selecting seeder location, initial velocity, mass and angular velocity are given. End point, bounce height, kinetic energy, and velocity can be calculated along the profile (Rocscience 2004b). The R_n and R_t values were found to be 0.28 ± 0.06 and 0.72 ± 0.13, respectively, for profile 13 (Fig. 10) using back analysis. For profile 39, R_n and R_t values were 0.30 ± 0.13 and 0.64 ± 0.24, respectively (Fig. 10). The 2-D rockfall analyses were carried out along 43 profiles (Fig. 8) to define the rockfall end point. Because of the different material properties observed at the site, the R_n and R_t values obtained from profile 13 were used for the profiles between 1 and 17, and the R_n and R_t values obtained from profile 39 were used for the profiles between 18 and 43. The other parameters used in the analyses are given in Table 2. The 2-D rockfall analyses were performed (Fig. 11) separately along the 43 profiles for the original slope,

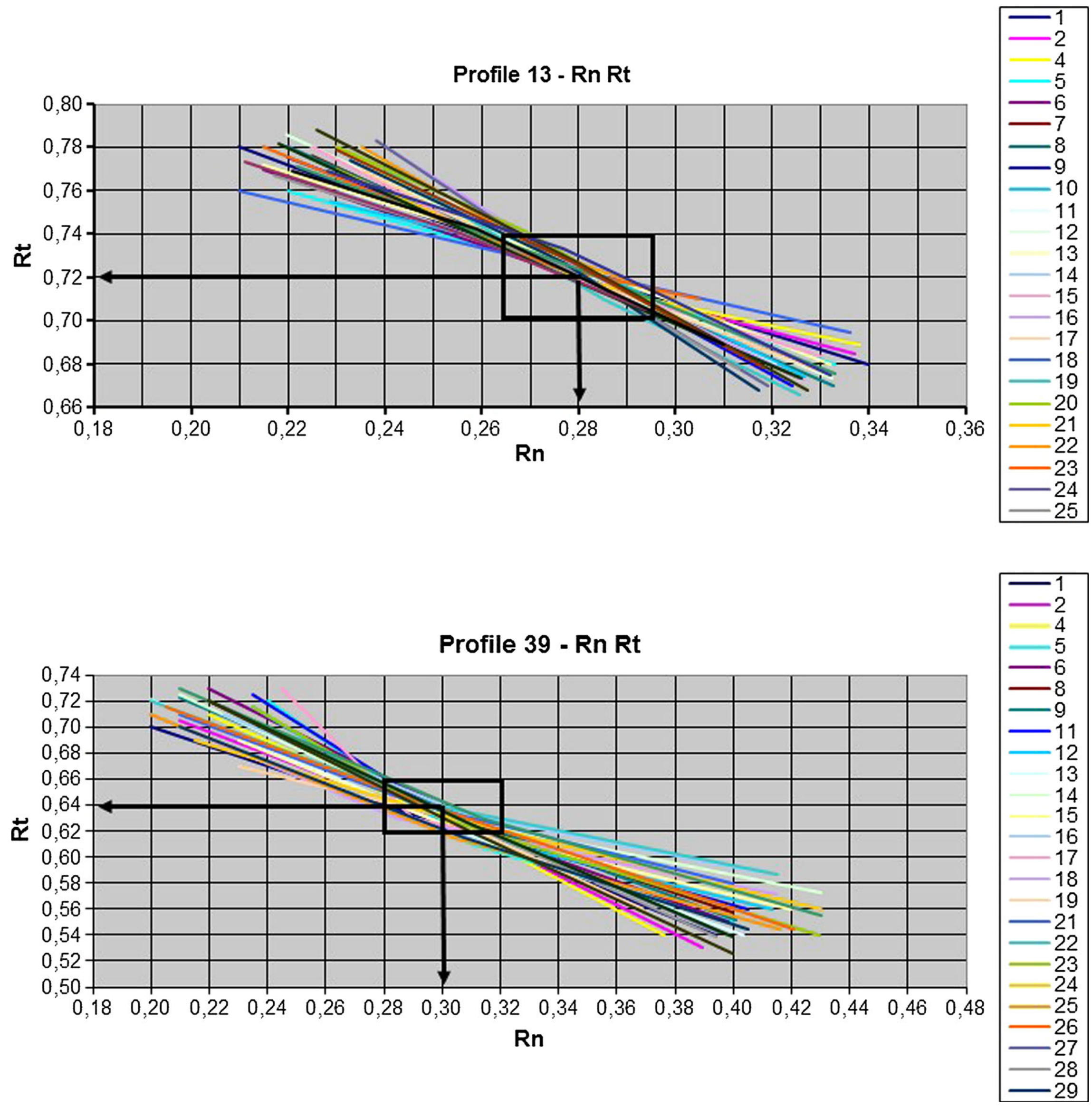
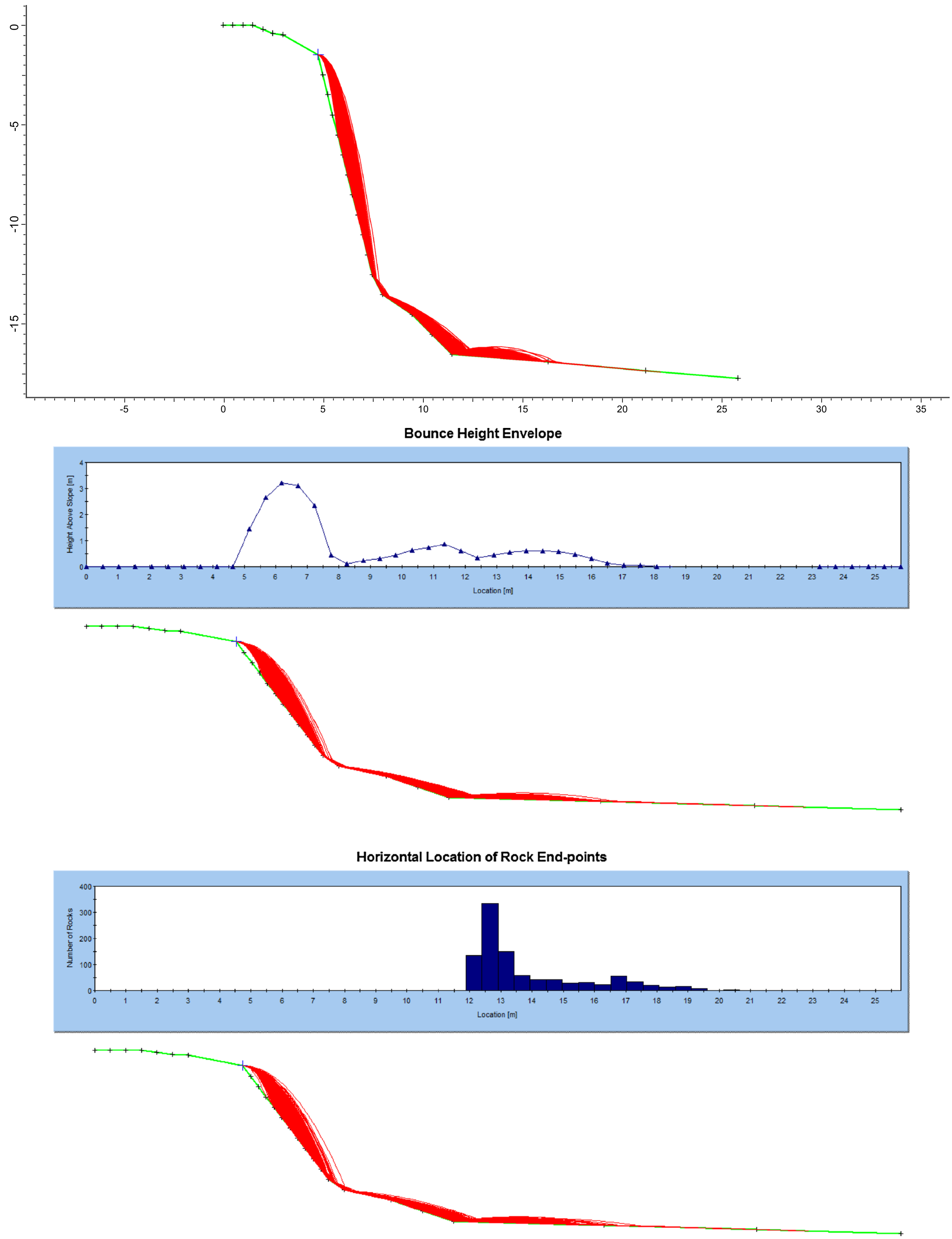


Fig. 10 The back analysis result for the profiles 13 and 39

Table 2 The parameters used in the 2-D rockfall analyses

Parameter	Value
Total number of fallen blocks	1000
Friction angle (°)	20
Slope roughness	0
Block weight (kg)	88
Initial velocity (m/s)	1.5
Minimum velocity cut-off (m/s)	0.1
Number of throws	1000
Sampling interval	100

inclined slope and benched slope. When the rocks were made to fall from the original slope, some of them went as far as the sea. This also applies to the inclined, and inclined with one-bench slopes. When the rockfall end points were considered for all slope conditions (Fig. 12), it became clear that the rockfall blocks act in falling mode and stop at a shorter distance in the original slope conditions. For the original slope, these blocks describe a falling mode style. On the other hand, rolling and bouncing movements are dominant in the other two slope conditions (inclined and benched slopes) and the end points imply a larger run-out. These slopes may therefore pose a danger for people near


Bounce Height Envelope
Height Above Slope [m]
Location [m]
Horizontal Location of Rock End-points
Number of Rocks
Location [m]

◀**Fig. 11** A typical 2-D rockfall analysis for the original slope of the 13th profile

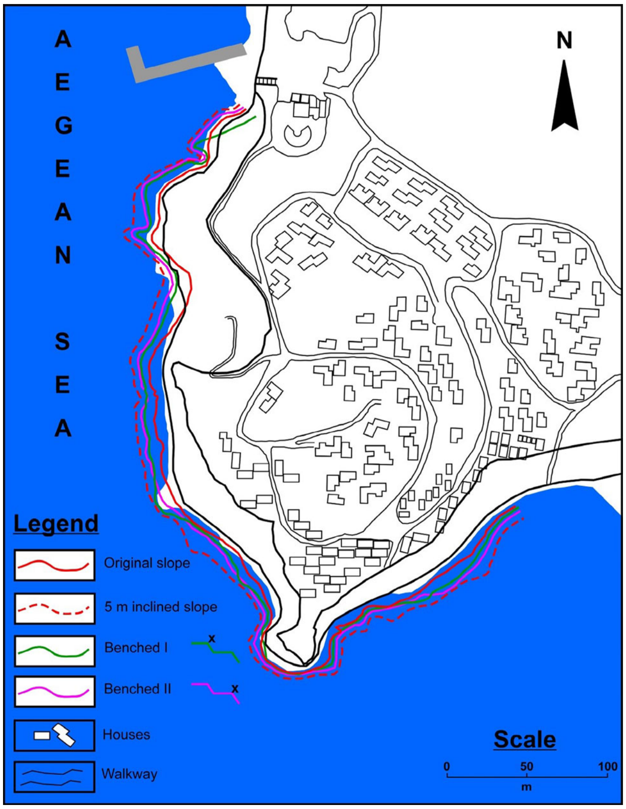


Fig. 12 Map showing rockfall end points obtained from 2-D analyses

the coast. Based on this, the profile of the existing slope must be preferred over the inclined and benched slopes. The maximum bouncing height is 5.75 m at the middle of profile 33 and the bouncing height significantly decreases near the coast. Therefore, a protective wall made of natural local stones should be considered at this site.

3-D analyses were performed using rotomap (Scioldo 1991) software for the original slope case only, due to the fact that slope flattening with or without a bench is not considered to be safe or feasible in this area. The Rotomap is a three-dimensional software that is used for rockfall analysis and for the design of protective systems. Simulating a large number of rockfalls and from the distribution of their average and maximum kinetic energies, it identifies the most effective places for the positioning of protective systems (GeoSoft 2005).

The first phase is a geometrical reconstruction of the slope. After definition of the topographic surface, geological and geomorphological data collections are necessary. The rockfall parameters used in the model are selected on the basis of the field conditions (Table 3). Stop point, average energy, maximum energy, minimum travel time, maximum height and volume are calculated.

Table 3 The rockfall parameters used in the 3-D analyses

Parameters	Value
Flying limit angle (°)	9
Colliding limit angle (°)	9
Bouncing limit angle (°)	9
Number of starting points	20
Number of initial velocities	10
Minimum initial velocity (m/s)	0.5
Maximum initial velocity (m/s)	1.5
Number of initial directions	5
Maximum angular deviation (°)	40
Boulder mass (*t*)	0.083
Normal coefficient of restitution (R_n)	0.28 and 0.30
Tangential coefficient of restitution (R_t)	0.72 and 0.64
Friction coefficient of boulders	0.5

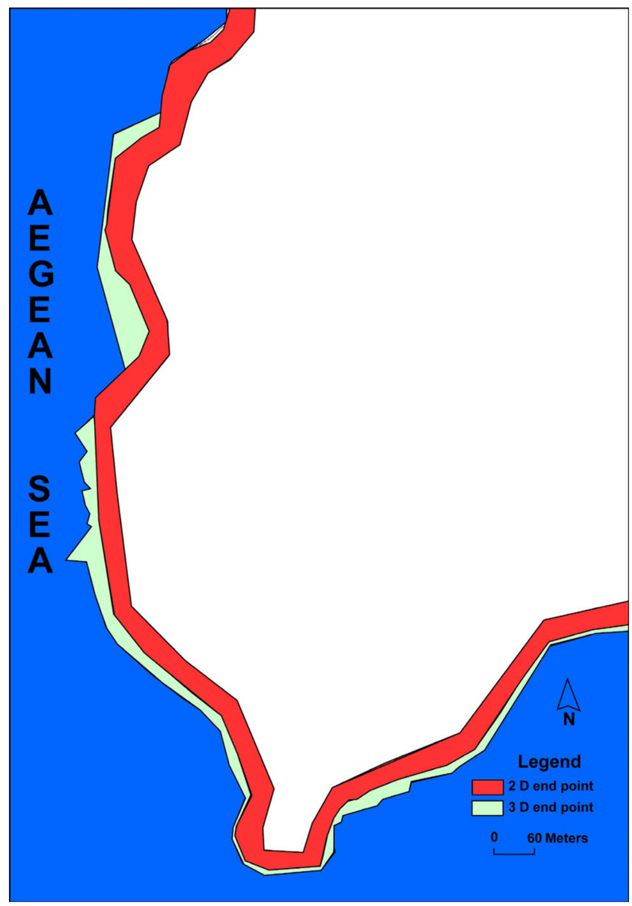


Fig. 13 The end point boundaries of 2D and 3D analysis for original slopes

The run-out distances obtained from 2-D and 3-D analyses for the original slope case show that there are some differences between the end points (Fig. 13) and bounce height values. According to the field observations and field

Table 4 The input parameters used in the rockfall models

2-D	3-D
Total number of fallen blocks	Flying limit angle (°)
Friction angle (°)	Colliding limit angle (°)
Slope roughness	Bouncing limit angle (°)
Block weight (kg)	Number of starting points
Initial velocity (m/s)	Number of initial velocities
Minimum velocity cut-off (m/s)	Minimum initial velocity (m/s)
Number of throws	Maximum initial velocity (m/s)
Sampling interval	Number of initial directions
R_n	Maximum angular deviation (°)
R_t	Maximum energy absorption capacity (kJ)
	Boulder mass (*t*)
	Height of the nets (m)
	Starting angle (°)
	Free-fall height (m)
	R_n
	R_t
	Friction coefficient

tests along profile 13 and 39, the 2-D model yields more realistic results. In the 3-D model, the stop points of the 43 locations (Fig. 8) are farther from the coast than in the 2-D model. This can be attributed to three main parameters, namely slope geometry, the algorithm of the software, and the input parameters used.

Slope geometry is important in terms of the direction and movement of the rocks. Small variability in slope geometry makes accurate prediction extremely difficult because small changes in the slope geometry may cause major differences in the results. For the 2-D model, the trajectory and slope are assumed to be a straight profile. The inclination of the slope and the surface roughness define the velocity of the rocks and movement type (rolling, bouncing or falling). In the 3-D model, the trajectory is not a straight profile. RocFall (Rocscience 2004b) is the software used in 2-D modeling to calculate the rock movement with particle analysis. The particle analysis can be divided into three main parts: the particle algorithm, the projectile algorithm, and the sliding algorithm. The validation of all simulation parameters and preparation of initial conditions are done by the particle algorithm. In the projectile algorithm, the rock has a velocity. To calculate the movement of the rocks, the sliding algorithm is used. Sliding of the rocks can occur at any part of the slope. For the purpose of the sliding algorithm, the slope segment or barrier that the rock slides on consists of a single straight profile segment that has the properties of slope angle (Θ) and friction angle (Φ) (Stevens 1998). For 3-D modeling, different algorithms are used. A comparison of the input parameters used in the programs is given in Table 4. These differences produce different results for the end point and bounce height values. Different input parameters also cause changes in the results.

General evaluations

As revealed by the rockfall analyses, the blocks falling from the cliffs in the study area can be dangerous, particularly if the end points are considered. In common engineering practice, rock blocks with a falling potential are removed at first. In a similar way, all rocks having the potential to fall as controlled by fracture must also be removed in the study area. The intact fallen blocks can be used in building a protection wall. After opening the area for public use, checks must be periodically performed at the end of each winter and the blocks that show a tendency to fall must be removed.

In the study area, there is a surface drainage line on the upper part of the cliffs but some deficiencies were observed in the surface drainage lines at some locations. Additionally, the drainage line turns with a right angle (Fig. 14) in the north of the study area (near profile 1 in Fig. 8) which renders it unsuitable for draining water. For these two reasons, new drain lines (top width = 50 cm, base width = 30, depth = 40 cm) must be built (Fig. 15) and the formers ones should be removed. In this way, the drainage lines, which must always be kept clear, will prevent the flow of rainwater into the cliffs.

The study area is quite green in comparison to its vicinity. Sliding and rockfall problems do not occur in those areas where a shrub kind of vegetation is very dense. For this reason, the greening of the poorly vegetated areas will

Fig. 14 Improper installation of the old surface drainage line

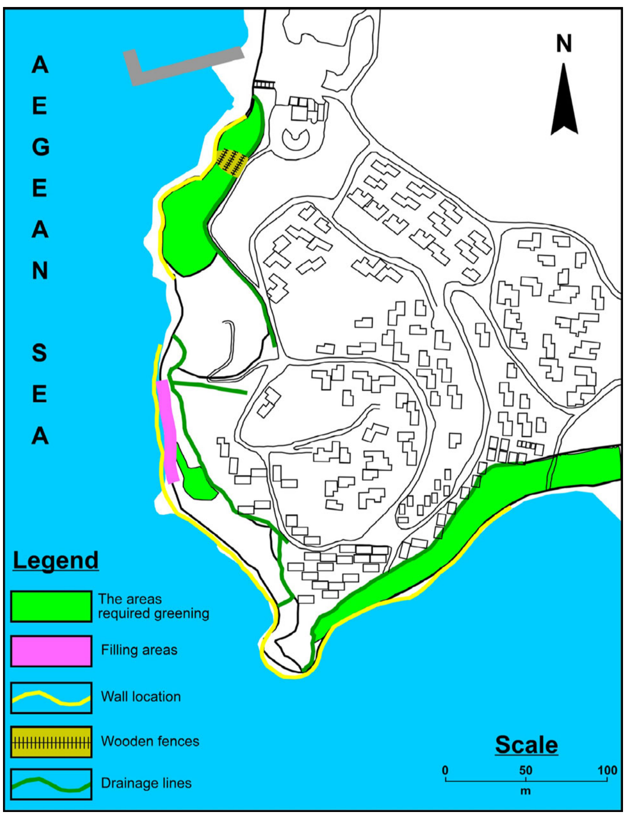


Fig. 15 Proposed remediation measures in the study area

not only improve the surrounding beauty but also reduce geological hazards (sliding, erosion, rockfall, etc.). Greening as recommended in Fig. 15 must be planned as soon as possible.

The rock units consisting of alternating sandstone–claystone–marl between profile 13 and 23 in Fig. 8 have been carved by wave action (Fig. 16). Small-scale collapses have occurred in the areas that have large caverns. Because these

Fig. 16 The rock units carved by wave action

caverns are potentially dangerous, they must be filled fully (Fig. 15) and as early as possible with natural stones.

According to the rockfall analyses of the study area, where rockfall occurs many blocks may reach the coast. This situation would be dangerous for tourists on the coast. The evaluation was carried out by considering the bounce heights of the rock blocks, and the nearest points to the coast where the energy of the block and bounce height attenuate were defined. The locations of optimal wall points (Fig. 15) were defined using this approach. Taking the environment into consideration, intact rocks found around the study area can be used to build the protective wall. It is proposed that the wall height for the whole area should be 1.5 m. Energy absorbers such as gravel should be installed, ensuring they have a thickness of $\sim$30 cm; these should be positioned at the back of the wall to attenuate the energy of blocks and decrease the bounce height. Provided the fallen material collecting behind the wall is removed every year, the wall is expected to function for many years. This wall will reduce the danger from rockfalls and minimize the undercutting formed at the coast. Vegetation can be applied to this wall, eventually covering the whole wall.

The slope in the north of the study area between profile 3 and 4 in Fig. 8 has the character of a soft soil rather than rock (Fig. 15). Here, soil erosion occurs occasionally, and densely spaced iron rods have been placed to prevent the erosion. This approach prevented the erosion to some extent but it has not been entirely effective because of the limited application area. Instead of iron rods, small terracing, wooden rods and deep-rooted vegetations should be used.

Conclusions and recommendations

This study aimed to investigate the slope instability problems of a touristic costal area and to mitigate the geological hazards by recommending solutions that were nature-friendly and accorded with the appearance of the slopes. The study area which will soon be open to tourism has steep and high cliffs near the coast. Geological field studies have shown that the flysch exists in the study area. It contains bedding plane and mainly two joint sets as major discontinuities. Laboratory studies show that the rock units have a moderate unit weight and porosity as well as low water absorption and point load strength values. The study reveals that rockfall is the main geo-hazard. Both 2-D and 3-D rockfall analyses indicate that many falling blocks may reach the shore and this situation would be dangerous for people in that location. To protect the tourists from these geological hazards, block removal, drainage, greening, cavern-filling, protective wall building and erosion prevention with small terracing, wooden rods and deep-rooted vegetations are suggested.

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