DOI: https://doi.org/10.68732/e68c13d7a79c407b

ISBN: 978-9989-2053-7-8

Rockfall Mechanisms at the Silivri Cliffs, Istanbul (Türkiye): Assessment and Mitigation

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Abstract

Rockfalls along coastal cliffs are a common phenomenon triggered by coastal erosion, heavy rainfall, earthquakes, and various human activities. If these cliffs are close to settlement areas, the associated hazard can quickly become a significant risk to civil life and infrastructure. Silivri Cliffs are located in the southwestern part Istanbul, Türkiye, 40 meters of height in average and exemplify a densely used shoreline. On the other hand, cliffs host to one of Istanbul's last known breeding colonies of the Lesser Kestrel (Falco naumanni). Since 2014, seven rockfall events have been officially reported along these cliffs. Geological material comprising Silivri Cliffs consists of Upper Oligocene-Miocene-aged, interbedded sandstone strata deposited within a regressive delta succession. In order to assess the failures in the area, an investigation was initiated with a 3D DEM visualization via photogrammetry utilizing drone images. Study continued with the identification of discontinuities and basic field tests to characterize the rock mass. Core samples obtained from field-collected blocks exhibit an average uniaxial compressive strength of 1.6 MPa and a unit weight of 19.29 kN/m³, while relatively stronger layers have UCS values of 37 MPa and unit weights of 24.73 kN/m³ in average. Initial kinematic analyses indicated that cliffs might experience planar sliding, wedge sliding, and toppling failures. Subsequently, joint-network-based 2D FEM analyses identified potential failure mechanisms and SRF values. Additionally, 2D and 3D rockfall analyses using RocFall and RocFall3 evaluated factors such as bounce height and total kinetic energy along trajectories. The results of analyses (e.g. low SRF values) well match with the observed failures. Rock mechanical and engineering geological interpretation regarding the use of shoreline by means of urban function and results of rock fall analysis encourage to design rock fall protection embankment against falling rock and rockfall protection fence applications including controlled trimming of some unstable rock blocks as mitigation techniques.

Keywords

Finite Element Method (FEM), Silivri Cliff (İstanbul), Slope Stability, 3D Rockfall Simulations.

1 Introduction

Due to the rapidly increasing population and construction in Istanbul, the risk of rockfalls turning into disasters is increasing. Mitigation strategies developed to prevent these rockfalls should be designed in a way that is compatible with the urban fabric (Ündül et al., 2026).Mass movements have been occurring for years along Silivri cliffs which is one of the most important historical and geological heritage sites in İstanbul (Fig. 1). These mass movements along the cliffs having an average height of 40 m, basically occurs in the form of varying rockfalls, threaten and harm human life, historical Silivri (Selymbria) Castle (Çiçek, 2019), recent settlements and other structures in the area.

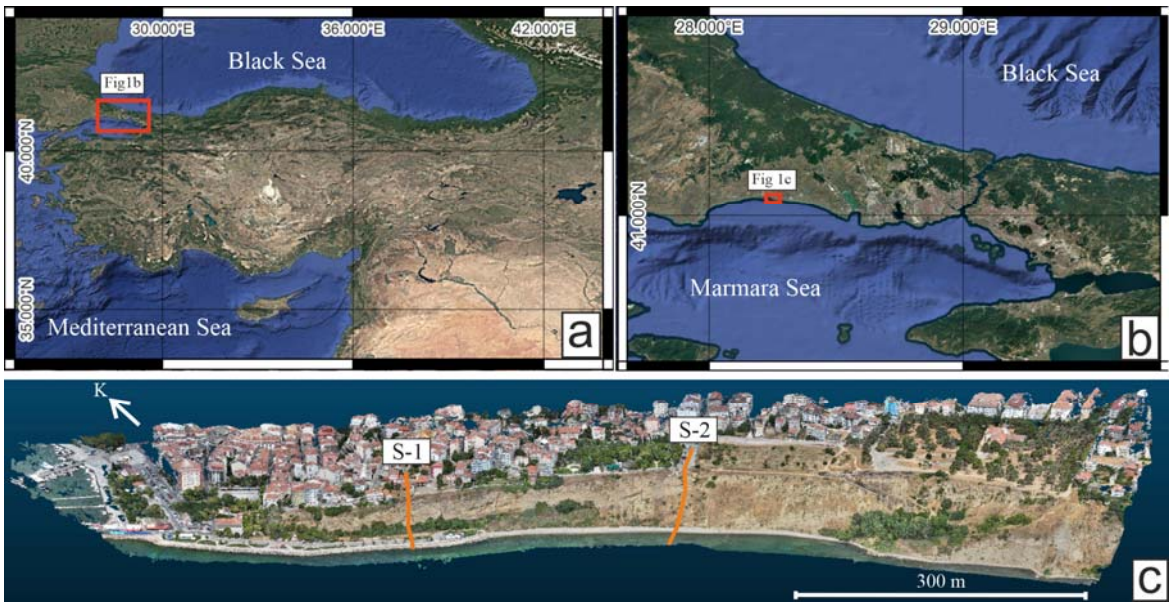


Fig. 1 Location map of the study area.

Rockfalls that occurred in the study area in 2024 and 2025 are shown in Fig 2. Regarding these rockfall events several remediation efforts have been attempted in the area, but the desired success in preventing and controlling mass movements has not been achieved. The preliminary stage of the study started by the research to understand the preparatory and triggering factors of these mass movements. Determination of the mechanism and defining failed and risky block dimensions including potential moving paths constitute the second stage. Results obtained from these studies help to suggest proper mitigation techniques.

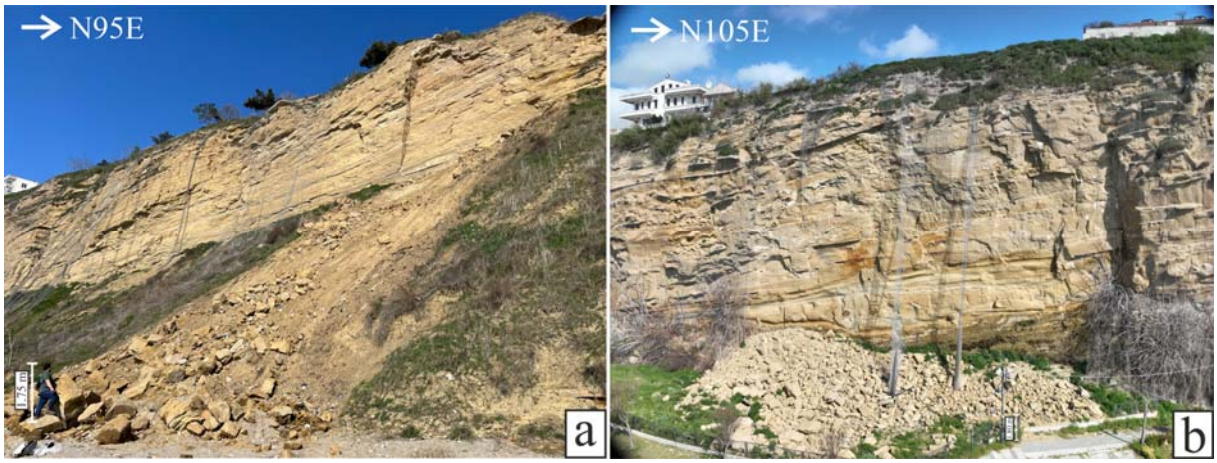


Fig. 2 Rockfall eventsalong Silivri cliffs (a) in July 2024 (appr. 200 m³ rock block failed) (b) in October 2025 (appr. 300 m³ rock block failed).

2 Geological Settings

The study area consists of sandstones formed in a regressive deltaic sequence during Upper Oligocene – Miocene (IMM, 2011; Fig 3). The main structural and sedimentological features of the cliffs are shown in Fig 3b. The study area is predominantly composed of weakly cemented, brittle sandstones. In addition, relatively stronger interbeds consist of carbonate-cemented sandstones are also observed.

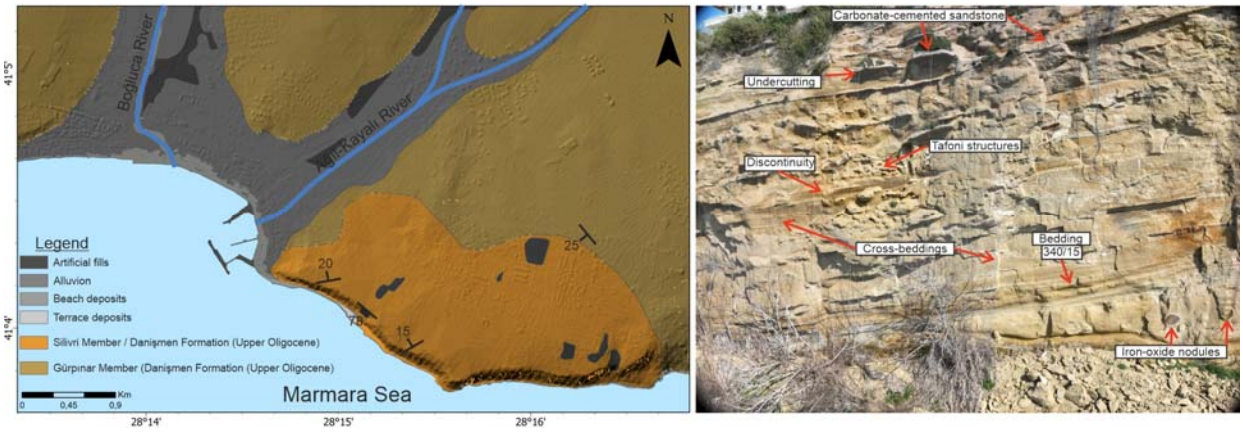


Fig. 3 The study area is shown in (a) a geological map (IMM, 2011) and (b) a photographic representation of structural and sedimentological features on the cliffs.

3 Methods

Initially, study focused on geological investigations. Subsequently, UAV photogrammetry was used to create a 3D DTM model of the vicinity of the study area. Following this, the rock mass forming the cliffs was characterized through field observations, field tests, and laboratory experiments basically following ISRM (1981 and 2007) suggestions. Regarding the findings, kinematic analysis (Markland Test) was performed using Dips software (Rocscience) to identify potential of slip mechanisms along the slopes. Furthermore, 2D FEM analysis was performed using RS2 software (Rocscience) to examine potential slip surfaces on the cliffs and determine the safety factor/strength reduction factor (SRF). The obtained topographic sections were imported to the RS2 software, and FEM analyses were performed using the Generalized Hoek-Brown rock mass parameters (Hoek and Brown, 2019) and Barton-Bandis discontinuity strength parameters (Barton, 2018).Finally, 2D and 3D rockfall analyses were carried out using RocFall and RocFall3softwares (Rocscience) to examine the changes in kinetic energy and bounce height values along the fall trajectories of the potentially falling rock blocks.

4 Kinematic Analysis

During field studies, the orientations of the discontinuities forming the rock mass were measured and transferred to the Dips software. The orientations of the discontinuities exhibit 5 major different sets of joints, as shown in Table 1. Kinematic analysis was carried out based on these data and results are shown in Fig 4. The general orientation of the cliffs has been determined as 86º/194º.

Table 1. Representation of the angle of inclination/direction of inclination values of joint sets in cliffs.

Joint No	1	2	3	4	5
Dip^{0} / Dip Direction^{0}	19 / 350	86 / 194	80 / 219	75 / 320	87 / 101

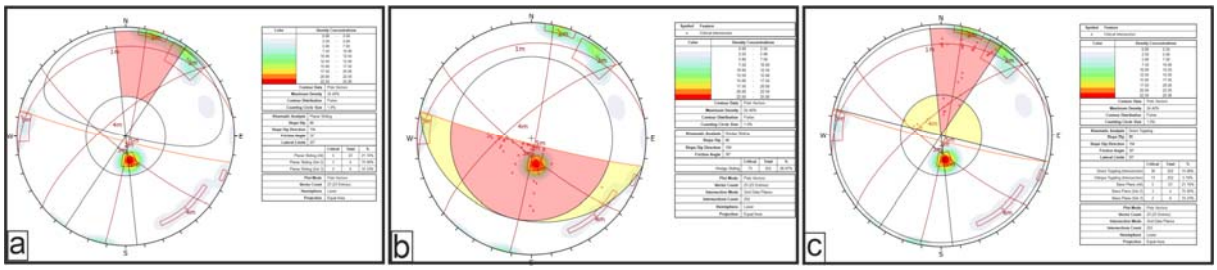


Fig. 4 According to the kinematic analysis results obtained using the Dips software, there is a potential for (a) planar slip, (b) wedge-type slip, and (c) overturning type failure to occur on the cliffs.

5 2D Joint-Network Based FEM Analysis

To determine the SRF value for the slopes forming the cliffs and to investigate possible failure mechanisms, 2D FEM analyses were performed. S-1 and S-2 topographic sections were considered (Fig 1) due to their critical slope angle and discontinuity properties.

Table 2. Rock mass parameters used for 2D FEM analysis in RS2 software.

Parameters	**UCS (MPa)**	**GSI**	**m_i**	**D**	**E_i(MPa)**	**JCS(MPa)**	**JRC**	**Φ_r**
Value	1.6	55	17	0	190	1.2	12	30

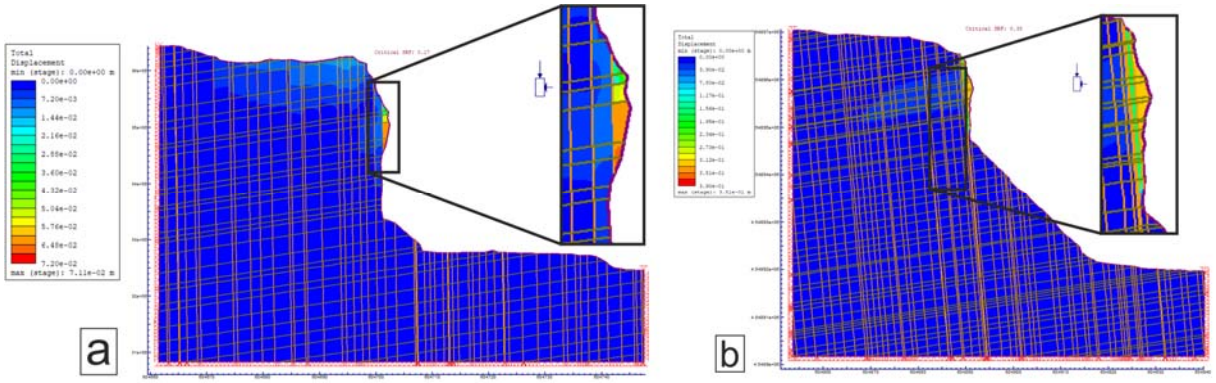


Fig. 5 According to the results of the FEM analysis, (a) the total displacement distribution of S-1 is shown (SRF = 0.17) and (b) the total displacement distribution of S-2 is shown (SRF = 0.38).

The obtained topographic sections were imported to the RS2 software, and FEM analyses were performed using the Generalized Hoek-Brown rock mass parameters (Hoek and Brown, 2019) and Barton-Bandis discontinuity strength parameters (Barton, 2018) as given in Table 2. As a result of these analyses, it was observed that the SRF value was 0.17 in section S-1 and 0.38 in section S-2.

6 2D Rocfall Simulations

The 2D rockfall parameters of the rockfall source-transition and accumulation zones were first determined using literature studies and the RocFall software library, and are presented in Table 3. Subsequently, rockfall analyses performed along the cross-sectional paths shown in Fig 6. The rigid body approach was used during the 2D analyses, and the actual geometries of the fallen blocks were drawn within the program. In both analyses, 1000 seeders were dropped, and the volumes of these seeders were determined as 0.25-0.5-0.75-1-2 m^3. Half of the dropped blocks represented weak-strength sandstones with a density of 19.29 kN/m^3, while the other half represented medium-strength sandstones with a density of 24.73 kN/m^3.

Table 3. Rockfall parameters according to the rigid body approach for different materials forming the slope and coastline.

Material		Bedrock	Soil with Grass	Soil with Vegetation	Asphalt	Beach Sand	Sea
Parameters							
Coefficient of Restitution	R_n	0.38 ± 0.04	0.4 ± 0.04	0.3 ± 0.04	0.44 ± 0.04	0.3 ± 0.04	0.01
	R_t	0.83 ± 0.04	0.8 ± 0.04	0.8 ± 0.04	0.71 ± 0.04	0.75 ± 0.04	0.01
Friction	Dynamic Friction	0.85 ± 0.04	0.5 ± 0.04	0.5 ± 0.04	0.56 ± 0.04	0.5 ± 0.04	0.9
	Rolling Friction	0.35 ± 0.04	0.45 ± 0.04	0.6 ± 0.04	0.42 ± 0.04	0.5 ± 0.04	0.9

According to 2D rockfall simulation results, the maximum kinetic energy value was observed to reach 1085 kJ for route S-1 and 894 kJ for route S-2. Based on the bounce height results, this value was found to be 3.05 m for route S-1 and 3.17 m for route S-2.

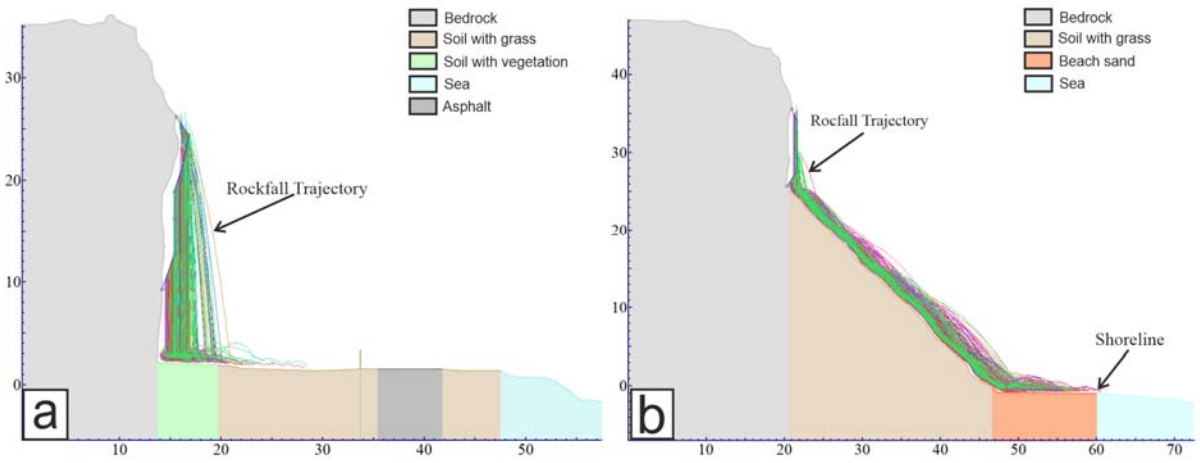


Fig. 6 Results of 2D rockfall analysis performed in RocFall software: (a) Results of analysis along the S-1 route; (b) Results of analysis along the S-2 section.

7 3D Rocfall Simulations

To investigate the trajectory behavior, total kinetic energy, and bounce height values of falling rock blocks under the influence of 3D topography, 3D rockfall analyses were performed. Unlike 2D analyses, the lumped mass approach was used in 3D rockfall analyses. The material parameters used for the 3D analyses are shown in Table 5. Similar to the 2D analyses, two different seeders were defined in the 3D analyses: 19.29 and 24.73kN/m³. A total of 5000 rock blocks with volumes ranging from 0.25 to 2 m³ were dropped as shown in Fig. 7.

Table 4. Rockfall parameters according to the lumped mass approach for the different materials forming the slope and coastline.

Material / **Parameters**		Bedrock	Soil with Grass	Soil with Vegetation	Asphalt	Beach Sand	Sea
Coefficient of Restitution	R_n	0.38 ± 0.04	0.3 ± 0.04	0.3 ± 0.04	0.4 ± 0.04	0.2 ± 0.04	0.01
	R_t	0.83 ± 0.04	0.8 ± 0.04	0.81 ± 0.04	0.9 ± 0.04	0.5 ± 0.04	0.01
Friction Angle	(º)	25 ± 0.75	14 ± 0.0.75	13 ± 0.75	6.3 ± 0.75	35 ± 0.75	0.9

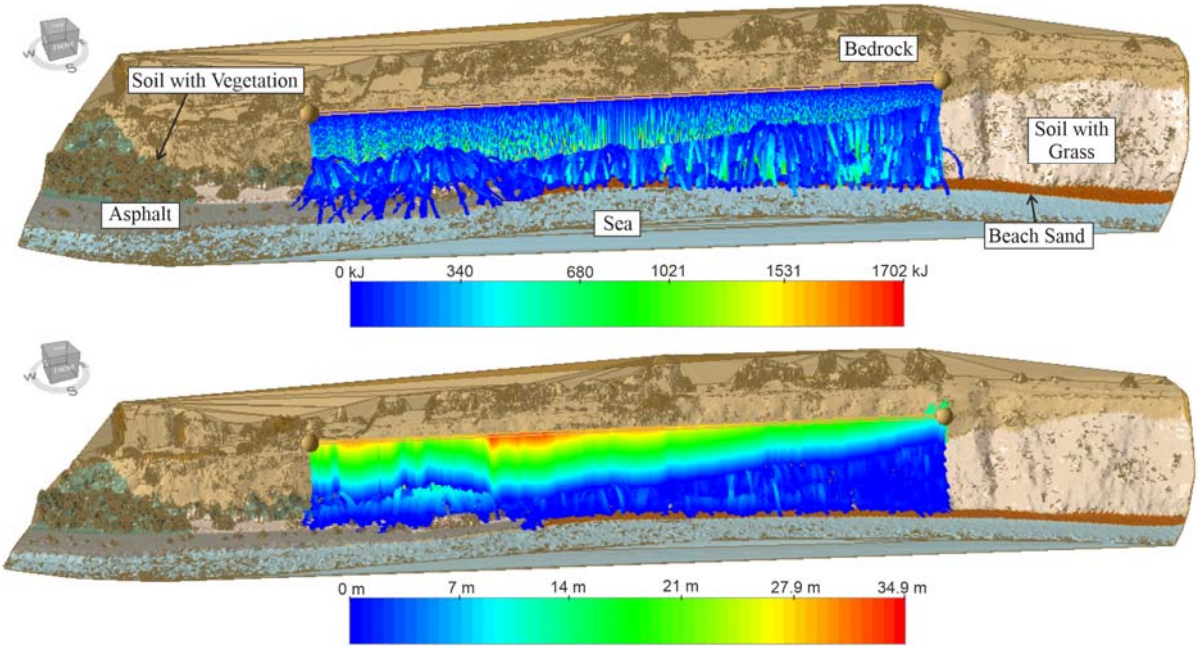


Fig. 7 The 3D rockfall analysis results are illustrated in the following figures: (a) the total kinetic energy distribution along the trajectories; and (b) the bounce height distribution along the trajectories.

Fig 7 shows 3D rockfall trajectories, which include the falling blocks' trajectories as well as the distribution of kinetic energy and bounce height along these paths. The total kinetic energy value at the moment the dropped rock blocks pass the potential barrier point is a maximum of 597 kJ, with a bounce height of up to 5.2 m.

8 Results and Mitigation Proposals

This study uses kinematic and FEM analysis to determine the frequency and mechanism of rockfalls in the Silivri cliffs. In addition, the trajectories of falling blocks, as well as changes in kinetic energy and jump height along these trajectories, were thoroughly investigated.

The result reveal that embankment for rockfall protection is essential. Besides to prevent rockfalls in the eastern section, where the shoreline is located, a 2000 kJ rockfall protection fence would be acceptable due to the short distance. Fig. 8 shows the proposed rockfall mitigation techniques for the cliffs. The steel meshes used here should be designed so that the little kestrel birds that live on these cliffs have access to and from their nesting spots.

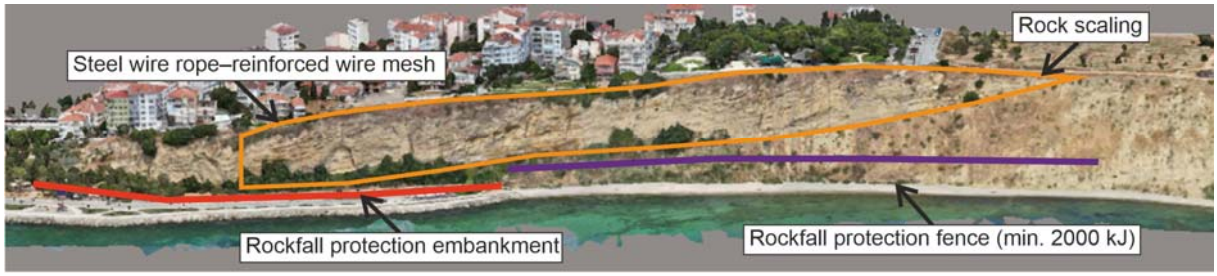


Fig. 8 Proposed rockfall mitigation techniques for the Silivri cliffs.

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