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INVESTIGATION AND REINFORCEMENT OF A WEATHERING INDUCED ROCK FALL EVENT

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Abstract

Increasing population and demand on housing increases the interaction of geo-environment and human settlements. Thus, the rate of natural events effecting daily human life surges for highly populated areas. A rock fall event occurred in a highly populated area in İstanbul (Türkiye). The source rock blocks belong to the Paleozoic sequence of İstanbul composed of nodular limestone with sandy-clay interlayers. These rock masses slided and fall a day after heavy rains. The study initiated by the examination of the dimensions of rock blocks and their paths and continued with the investigation of discontinuity and weathering properties. Geomatic studies established numerical 3D view of the area based on drone views. Field observations showed the effect of the growing roots of trees within discontinuities. This weathering effect exerted stresses along discontinuities. Laboratory studies showed that the rock has moderate uniaxial compressive strength (40-51MPa). Numerical models obtained from various cross sections demonstrated the most critical sections to be considered and reinforced. Study advices pre-cleaning of risky blocks after a fence production on the potential falling paths, rock anchors in some localities with varying lengths. These mitigation processes were then re-assessed with numerical models showing that the factor of safety increased to desired levels.

Key words

FEM Analysis, Mitigation, Rock fall, Urban Areas, Weathering

1 Introduction

Rock falls are natural events that mostly occurs in rugged and mountainous terrain, cut-slopes and open-pit mines. These events have impact on human life and engineering structures. As well-known rockfall is defined by Varnes (1978) as the very rapid and sudden movement of rock blocks separated along discontinuity surfaces on slopes due to gravity. The fundamental reason for these sudden instabilities in rock masses is that the peak shear strength on the discontinuity surfaces can easily drop to the residual shear strength as a result of a few millimeters of displacement (Wyllie and Mah, 2002). This event can be triggered under various effects such as freeze-thaw, wetting-drying cycle of water along discontinuities, heavy rains, growth of tree roots, weathering and seismic effect etc. exhibiting a free fall down steep slopes, rolling and/or jumping of blocks depending on the steepness of the slope (Ritchie, 1963; Wyllie, 2015). Blocks that remain stable for years in rock slopes can suddenly separate from the mass and tend to move downwards. In order to properly design reinforcement and/or landslide mitigation works techniques, engineers need data including dimensions of rock blocks, impact loads, travel distances, jump heights etc.

Such an event occurred in the flanks of Bosphorus strait on 02.10.2023 (Figure 1 and Figure 2). Rock fall initiated in an area approximately of 20x10m. It was observed that the rocks were distributed laterally for 40 meters at a distance of approximately 80 meters away from the detachment zone. The site comprises many priceless historical buildings. On the other hand, unfortunately there are some buildings constructed without any engineering design and any approval from authorities. Thus, these latter buildings have huge potential even to collapse without any major impact (rockfall, seismic event etc.). Some of these buildings were already damaged during the rockfall event (Figure 2). Along the Bosphorus strait, due to official, visual and environmental restrictions engineers force to define environmentally friendly designs. This research and engineering application define a systematic reinforcement methodology especially for such steep slopes in densely populated area where environmental and visual expectations should be considered.

Figure 1. Location Map of the Study Area (İstanbul-Türkiye).

The trend of the slopes in study area are north-east and south-west direction (Figure 1). Since there are actively used pedestrian paths and dense settlements under the risky slope, rock falls threaten the safety of life and property. To analyse different risk situations regarding the potentially unstable rock geometries the study area was analysed in three zones (Figure 3).

i. Block Rockfall (Zone A - area with relatively large blocks - approximately more than $1m^3$)
ii. Rocks with relatively smaller dimensions and debris slides (Zone A and Zone B - area with relatively smaller rock blocks and potential of debris flow of varying natural and man-made material)
iii. Rubble due to risky structures and building components (Zone B - area with structures and building components)

It is clear that the collapsed building component are suspended in different positions on the slope, which has a potential risk to slide (Figure 2 c and d).

Figure 2. Views of a) failed blocks b) closer view of nodular limestone c) damaged building d) risky natural and man-made debris material.

2. Methods

The initial stage of the study comprises generating surface model and base maps of the study area using photogrammetric methods. Simultaneously, geological and engineering geology properties were determined following the definition of physical and mechanical properties of the rocks by laboratory studies. Index and mechanical results were determined according to ISRM (1981 and 2007) suggestions. In addition, kinematic analyses were performed based on discontinuity measurements of the slopes. Depending on these data geotechnical numerical model of study area was prepared and slope stability analyses were carried out using finite element method (FEM). With the help of 1,200 different probabilities on the sections prepared from the digital terrain model of the study area, the jump height, speed and total kinetic energy possibilities of the possible falling rock blocks were calculated and evaluated. Reinforcements and precautions were than proposed.

3. Numerical 3D Model of the Area

Detailed topographic data are very important in rock fall events both in analyzing the rock fall event and stability analysis before and after precautions. The aerial photographs obtained from an unmanned drone were evaluated with the stereoscopic method. Point cloud and vector data were compiled to generate 3D numerical model with contour lines (Figures 3).

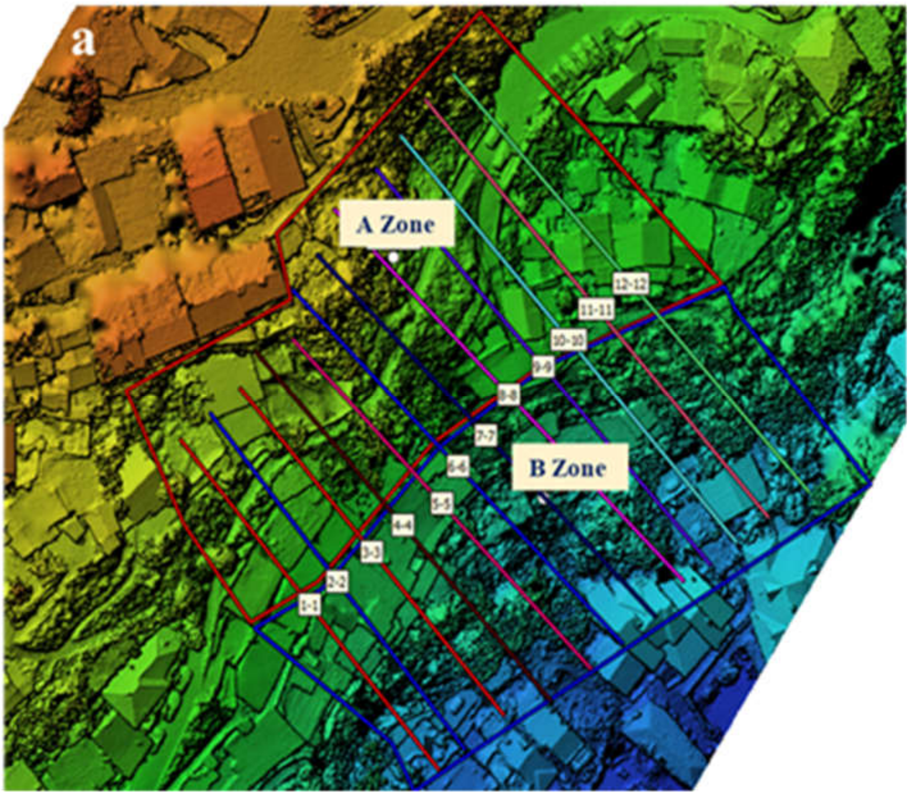

Figure 3. Digital elevation view on the 3D terrain model showing studied zones and critical rockfall routes (e.g. 1-1, 2-2 etc. in varying colors) (note that the resolution of the orthophoto is 1.35cm/px).

4. Geological and Engineering Geological Properties

The rocks in the study area belong to the Istanbul Paleozoic. The unit is known in the region as Ayineburnu Member (Dcda) of Denizli Köyü formation (DCd). Upper Devonian aged Dcda is a limestone-claystone succession of different strengths. The unit gained a lumpy appearance with a boudinage structure during the diagenesis process (Figure 2) thus named basically as nodular limestone. The rock mass was fractured by tectonic events and weathering. The effect of root on discontinuities are very evident. The growing roots within the apertures of discontinuities decreases the shear strength. This process is unfortunately very common on the site (Figure 4). These biological and physical weathering effects play a major role in the stability of the rock mass.

Figure 4. View of the effects of plant roots along discontinuities.

The distance between the discontinuities is approximately 200cm on average (varying between 80-400cm) and the discontinuities are mostly closed. Open discontinuities range from millimeters to 10 cm, especially in areas where plant roots penetrate deeply. The continuity of almost all of the discontinuities, except for discontinuities due to weathering in the sections close to the surface, can be observed throughout the outcrop. Discontinuities are wavy-smooth and slightly rough (JRC 6-8). Water seepage has been observed in areas close to the surface along the discontinuities during rainy periods. The rock mass can be considered as slightly and moderately weathered according to ANON (1995).

The effective ground acceleration value of the study area was obtained from the Turkey Earthquake Hazard Map, and the maximum ground acceleration value was determined as 0.325 g and was considered in the calculations.

Field studies and observations reveal that some blocks on the slope had previously fallen and some risky blocks are standing with a potential of a fall or slide. Thus, further studies were carried out and their results are given below.

5. Kinematic Analysis

Kinematic analyses were performed with Rocscience Dips (2024) software. Both field observations and discontinuity orientations in the study area show that planar and wedge-type movements may develop. The kinematic analysis of the rock mass considered planar and wedge type instabilities (Figure 5). The safe slope angle is 32° for planar shear and 37° for wedge type instability. Reducing the general slope angle of the rock mass to 37° will completely prevent from possible instabilities. However, since this is not possible due to the surrounding construction, risks must be eliminated with local intervention and protection structures in risky blocks and areas.

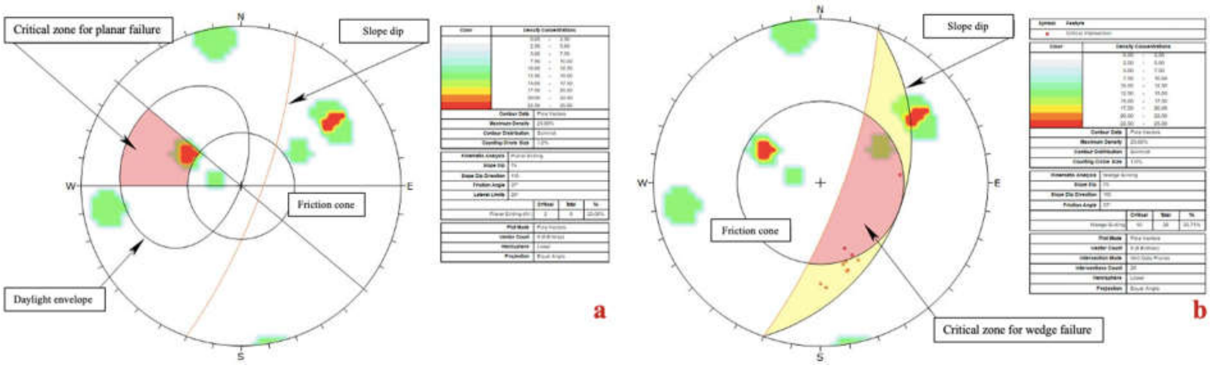

Figure 5. Kinematic analysis a) Plane type stability analysis of rock mass, b) wedge type stability analysis of rock mass.

6. Slope Stability Analysis by Using Finite Element Method

In order to determine the stability condition, the finite element method "RS2 v.11.023" (Rocscience, 2024) program was used and total displacement analyses were performed with the critical SRF (Stress reduction factor) value. Stress-strain analyses were performed using the failure criterion suggested by (Hoek et al. 2002) and plastic failures were investigated. Seismic loads were also considered in the numerical analyses and the horizontal ground acceleration value was determined as 0.325g.

For geomechanical conditions, the horizontal vertical stress ratio was chosen as 0.4 in both static and dynamic calculations. Geotechnical parameters calculated according to Hoek-Brown (2018) Failure Condition and GSI are presented using field observations and laboratory test results. The parameters used in the numerical analysis are given in Table 1.

Table 1. Geotechnical parameters for nodular limestone

Geomechanical Parameter	Value
Unit Weight (MN/m^3)	0.025
Young Modulus (MPa)	596.52
Poisson Ratio	0.3
Uniaxial Compression Strength (MPa)	30
Geological Strength Index (GSI)	41
D (Disturbance Factor)	0.7
m_b	0.274
s	0.0002
a	0.511

Critical slopes of the study area were evaluated with the finite element analysis method, and the total displacements are given in Figures 6a-c-e under static loads, and in Figures 6b-d-f under dynamic condition. Long-term slope stability analysis was carried out under current state and dynamic loads by applying the Shear Strength Reduction (SSR) shear stress reduction method in numerical calculations.

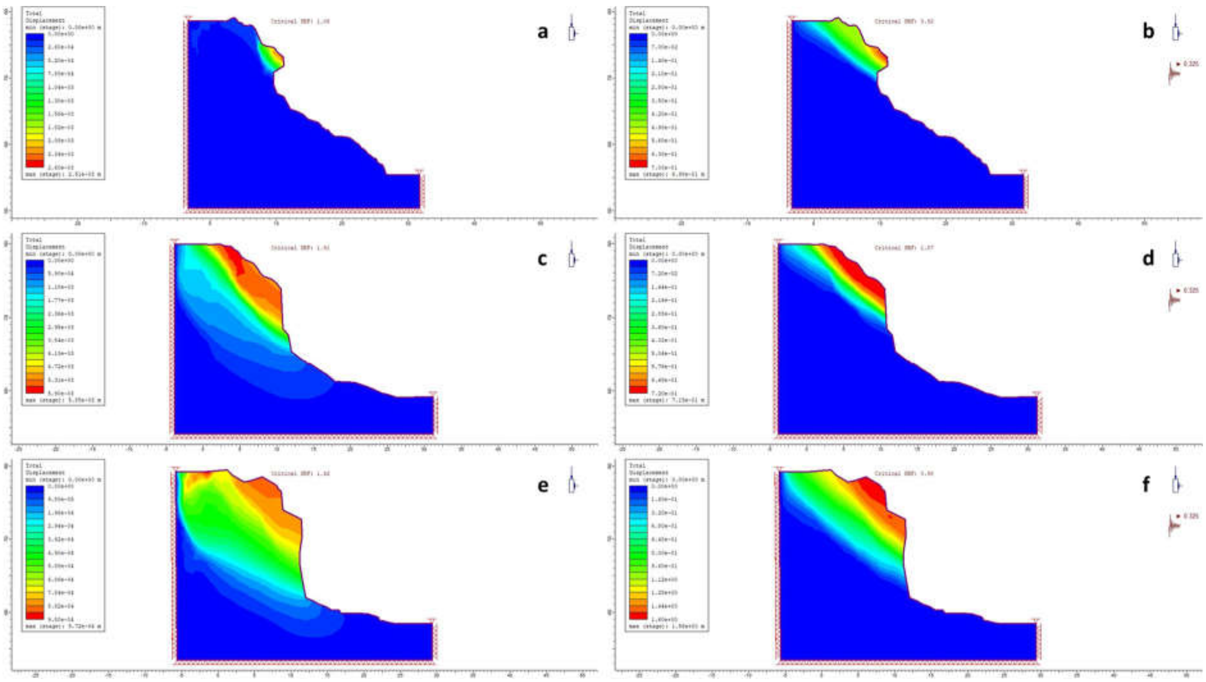

Figure 6. Total displacement a) for static condition along section K1-1 b) under dynamic conditions along section K1-1 c) for static condition along section K2-2. d) under dynamic conditions along section K2-2 e) for static condition along section K3-3 f) under dynamic conditions along section K3-3 (Please refer to Figure 3 for cross section routes)

The analyses showed that the slopes have SRF over "1" under static conditions. But decreases below "1" in dynamic conditions. Under static conditions the displacement is expected to be less than 0.26cm whereas it may rise to 70cm under dynamic conditions. This shows that some parts of the study area will be unstable in the event of an earthquake. In this study, SRF values obtained for static and dynamic situations are accepted as Safety Factor (SF).

7. Rock Fall Analysis

As a result of preliminary analysis, the 12 most critical routes for rocks that may fall were determined on the 3D numerical model prepared with photogrammetric methods. Figure 3 shows the most critical routes of rockfall. Rock fall analyses were carried out in the RocScience RockFall (2024) program by taking cross-sections of the determined routes.

In rock fall analyses, material parameters were determined depending on the geological structure of the slope along the route (Table 1). The factors that directly affect rock fall analysis results are the recovery coefficients (Rn, Rt) and friction angle. Coefficient of normal and tangential restitutions Rn and Rt values, which control the energy dissipation at the points where the falling block contacts the topography, were defined in the sections in accordance with the lithological situation on the slope. Clean hard bedrock feature and parameters were defined for the routes in the RocFall program, depending on the land situation nodular limestone surfaces. In the software, bedrock outcrops (weathered limestone) feature and material parameters were defined in areas with weathered nodular limestone surfaces, depending on the terrain along the route.

7.1. 2D Rock Fall Analysis

During site investigation, it was observed that the risky rock blocks and previously failed rock blocks exhibit varying volumes (0.25-6m³). In addition, the risky blocks in Zone A has volumes of approximately 15-20m³. The slope geometry and discontinuity properties along routes 1-1 and 3-3 reveal that risky blocks have a volume of approximately 1m³ and a mass of 2450 kg. Considering discontinuity properties along remaining nine routes, the largest block size was determined as 6m³. and an average weight of 14700 kg. A totally of 1200 different rock fall analysis scenarios were calculated by solving the jump height of rock blocks, total kinetic energy and the maximum distance. Results revealed that rocks can reach with 100 different possibilities for each route. Maximum jump height and total kinetic energy values obtained from rock fall analyses are given in Table 2.

Table 2. Block Weight, Initial Speed, Maximum Jump Height and Total Kinetic Energy Values in Rock Fall Analyses along the Route.

	Section No:	1-1	2-2	3-3	4-4	5-5
1 m³ and 2,450 kg Block	Risky Block Mass (kg)	2,450	2,450	2,450	2,450	14,700
	Initial Fall Speed (m/s)	1.00	1.00	1.00	1.00	1.00
	Maximum Bounce Load Upon Impact with the Road (m)	1.96	2.48	2.68	3.14	3.80
	Total Kinetic energy at the moment of hitting the Road (kJ)	83.35	150.05	114.30	449.32	2132.2
	Section No:	6-6	7-7	8-8	9-9	10-10
6 m³ and 14,700 kg Block	Risky Block Mass (kg)	14.700	14.700	14.700	14.700	14.700
	Initial Fall Speed (m/s)	1.00	1.00	1.00	1.00	1.00
	Maximum Bounce Load When Hitting the Barrier (m)	5.51	5.59	5.93	3.05	2.05
	Total Kinetic energy at the moment of hitting the barrier (kJ)	4,219.7	1,708.2	3,639.4	3,175.1	4,516.3
	Section No:	11-11	12-12			
6 m³ and 14,700 kg Block	Risky Block Mass (kg)	14,700	14,700			
	Initial Fall Speed (m/s)	1.00	1.00			
	Maximum Bounce Load When Hitting the Barrier (m)	3.38	8.46			
	Total Kinetic energy at the moment of hitting the barrier (kJ)	4,414.3	4,489.5			

The analyses reveal that 90% of the falling blocks can reach the settlements. Although the rock block reaching the residences at the most critical section in the rock fall analysis has a kinetic energy of approximately 4,500 kJ, and average speed of 24.10 m/sec and a maximum jump height of 10 m and an average of 3-4 m height along the routes. The geometry of the slope hinders the work of some large vehicles. For these reasons some risky blocks should be broken and removed from the slope with a fully controlled rock crushing application and then supported with reinforced combined nets and rock bolts.

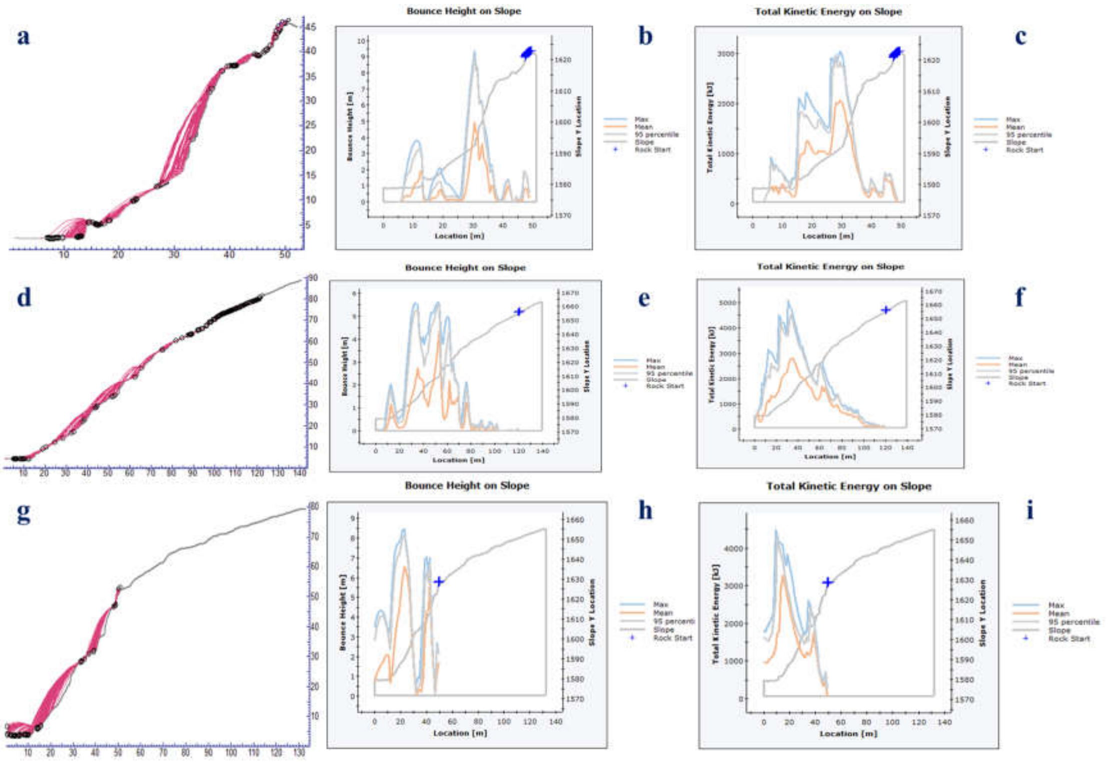

Figure 7. Scenarios that may occur during rock fall along routes No 5, 10 and 12 (left column show the calculated jump heights, mid-columns show the bounce heights, right column shows the kinetic energies).

8. Conclusions

The study investigated a rock fall event on 02.10.2023. The rocks belong to Paleozoic sequence of İstanbul. These old rocks were deformed under tectonic stresses. Besides, these nodular limestones are subjected to biological and physical weathering. Thus, discontinuities of varying properties exist.

The investigation initiated with the construction of precise digital surface model of the study area utilizing orthoimages. Stability analysis exhibit the kinematic admissibility. Rock fall analyses utilizing 3D model defined major rock fall paths, speed, impact energy and the jump height of potential falling rocks. According to these findings five stage reinforcement methodology was proposed for the site as follows;

- ***Construction of fens barrier,*** rockfall analysis reveal that 90% of falling blocks reach the settlements. This is unfortunately confirmed by the event occurred in 02.10.2023. Prior to any reinforcement works fence barriers was proposed as a must in order to ensure the security during construction. Fence barrier will remain as a permanent precaution thus will play an important role in any instabilities that may occur in time.
- ***Fully controlled rock breaking and detailed slope cleaning,*** all risky rock blocks that has potential to fail (i.e. highly weathered, deeply penetration of roots etc.) must be broken or cleaned and removed from the slope in a controlled manner.
- ***Reinforced combined net,*** the investigated entire slope will be fixed with a reinforced combined net. The nets will be anchored to the deeper and durable rock slope.
- ***Supporting Risky Blocks with Rock Bolts,*** in addition to previous reinforcements blocks with considerably higher volumes (volume of 96.52 m³ and total weight as 236.48 tons) will be anchored to the rock mass with rock bolts.
- ***Monitoring.*** After applying the precautions, the reinforced slope was reevaluated with numerical models concluding the increase (the recalculated safety factor is at least 1.1 in dynamic condition and the static safety factor will be at least 3). At the latest stage, due to the importance of the study area it is strongly recommended to monitor the reinforcement system and the slope stability.

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