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A CASE STUDY: COST-BENEFIT AND RISK ANALYSES OF GABION WALL FOR ROCKFALL PROTECTION METHOD IN BOZKIR, TURKEY

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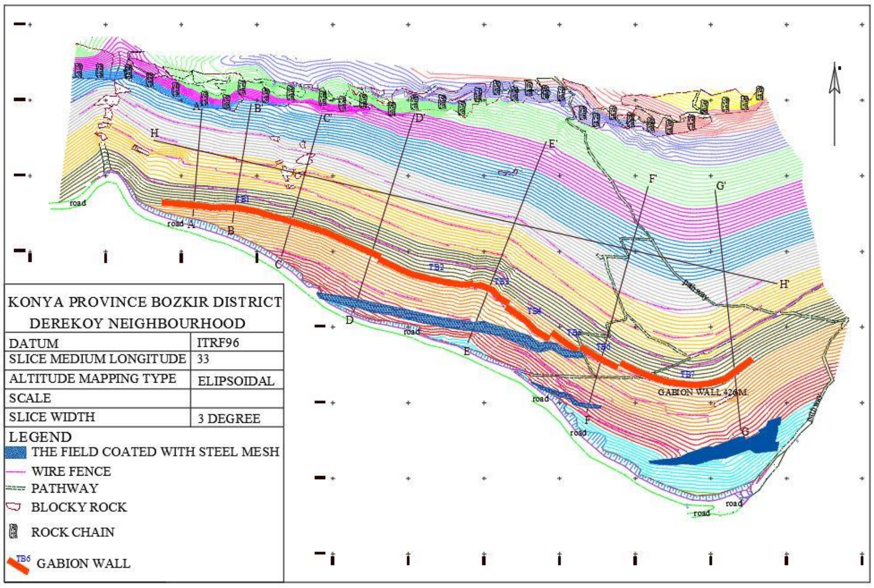
Highlights

- The geographical, geological, meteorological, and topographic features of the mountainous terrain affect the decomposition of rock masses from the bedrock.
- The possible rockfall scenarios of the rock masses scattered in the mountainous area were determined and precautions were taken.
- Total kinetic energy, bounce height, and translational velocity of falling rock masses were taken into account for the design of gabion wall.
- The rockfall analysis shows that the rocks (2500 kg) on the slope will reveal energy of 400-500 kJ, and the splash heights may vary between 30-150 cm.
- 420m-length and 3m-height gabion wall has 10000 kJ energy damping capacity was constructed to eliminate the risk of rockfall for 150 houses in the region.

Graphical Abstract



Location of gabion wall to prevent rockfall in the case of Dereköy/Bozkır

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ABSTRACT: The construction of residential buildings, highways, and dams in the areas under the risk of rockfall constitutes a significant threat to life and property safety. Previously, the easiest solution for rockfall protection was to move the settlements in the regions under rockfall risk to another location although it was expensive. Another method is removing the rocks by hand, machine, or using explosives, since it is dangerous. Nowadays, various rock improvement methods of constructing barriers exist due to the developing technology and facilities. In the study, to resist the rockfall, a case study on analysis of a gabion wall in the Dereköy neighborhood of Bozkır District in Konya was presented. In the preliminary design stage, mapping studies, rock kinematic analyses, and the possible rockfall scenarios in the study area were carried out to determine the current conditions of the land before the construction works. The rockfall analysis shows that the rocks on the slope will reveal energy of 400-500 kJ, and the splash heights may vary between 30-150 cm. As a result of this data, a 420m-length and 3m-height gabion wall was constructed. The gabion wall, which has a 10000-kJ energy damping capacity, eliminates the risk of rockfall for 150 houses in the region. A huge cost-benefit has been achieved by constructing a gabion wall instead of other methods (expropriation of 150 houses or the surface coating with steel mesh) as a precaution against the hazard of rockfall in the study area.

Keywords: *Gabion Wall, Kinematical Analysis, Rockfall Hazards, Slope Stability*

1. INTRODUCTION

Rock slope stability problems occur in the mountainous geography nearing the settlements and transportation structures. Rock slope failure may occur in two ways: falling-overturning and sliding. Falling-overturning type failure problems generally occur in natural slopes, but sliding-type failures usually occur in areas intervened by human hands and cut-off slopes [1], [2]. Rockfalls are unpredictable and suddenly develop. As a result of natural events such as wind, temperature, pressure, and water erosion, the rock blocks with low abrasion resistance lose their support from the upper rock blocks, and then falling occurs [3], [4], [5], [6], [7]. Moreover, resulting from exposure to freeze-thaw cycles of water that fill into the cracks inside rocks, the rocks break down, and then rockfall occurs [8], [9], [10]. The hazard of rockfalls can be prevented by increasing slope stability and designing slopes correctly.

In the literature, the rockfall failure types are classified by Rockfall Hazard Rating System [11], [12], [13], the Rock Engineering System [14], [15], [16], [17], and IMIRILAND [18], [19], [20]. In most rock slope stability problems, geometric relationships between discontinuities in rock blocks are evaluated [21], [22], [23], [24]. Slope stability analysis can be performed by methods such as numerical analysis [25], [26], limit equilibrium analysis [27], slope mass grading [28], [29], and kinematic analysis [30], [31], [32]. Kinematic analysis is used in cases where failures in rock slopes are controlled by discontinuities [33], [34], [35]. By kinematic analysis, possible types of failures (wedge, planar, and circular types of sliding and overturning) can be investigated. In the rock slope stability analysis, the incline and height of slope and discontinuities

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should be determined [36], [37], [38]. It is well understood that the most important parameter affecting the safety factor of rock slope stability is the cracks in the slopes [39], [40], [41].

Gabion walls are gravity-type retaining structures. Construction of these structures is done by placing large cages filled with stones or rocks in a specific order until they reach the height of the wall. Since gabion cages are formed with steel wire mesh, which is hexagonal double-twisted, and zinc-coated, they act as reinforcement and have high resistance to tensile and shear stresses. In addition, while deforming due to the loading condition, the structural elements share the load within themselves, making it easier to redistribute the load [42]. Since it has a porous structure, water does not collect behind the wall, providing an advantage to stability [43]. They can be built quickly without special equipment and skilled personnel. Detailed information on the design of gabion walls can be found in the study of Chikute and Sonar [44]. The standard specification of gabion steel wire mesh is reached in ASTM A975-11[45]. Gabion walls are used as a retaining structure to ensure the stability of structures such as roads, railways, bridge abutments, and inclined grounds, and to prevent erosion and flooding. These structures can also be used as a barrier against the danger of rockfall due to their high resistance. The stability of gabion walls has been investigated by many experimental and numerical studies [46], [47], [48]. The efficacy of gabion walls to resist 100 kN rock blocks having 4000-8000 kJ of impact energy is demonstrated by numerical analysis [49]. Gabion walls have high energy damping capacity and are capable against multiple strikes of rock blocks without any requirement of repair [50], [51]. In addition, gabion walls are more advantageous in terms of cost-benefit compared to reinforced concrete retaining walls of the same energy-damping capacity [52]. However, the case study in which it is designed as a barrier against rockfall and applied in the field is quite limited [53], [54]. The rock reclamation method to be selected varies according to the topographical condition of the land, rock properties and the nature/importance of the structures in danger. Therefore, the precautions to be taken against each rockfall incident are specific to the project conditions.

Rock slope failures occur as falling-overturning type failures in the Dereköy neighborhood of Bozkır District in Konya, Turkey. In the present study, rock slope stability analysis was carried out using the kinematic analysis. The velocities, total energies, and bounce heights of the falling blocks were evaluated using the Rockfall computer software program. The protection methods that can be used against the rockfall hazard are compared for barrier and non-barrier situations. Resulting of the cost-benefit analysis, a gabion wall, whose length, height, and energy-damping capacity are 420 m, 3 m, and 10000 kJ, respectively, was built in the study area against the rockfall risk.

2. DESIGN OF THE ROCK FALL PROTECTION STRUCTURES

Slope instability is the most critical hazard in mountainous areas. It includes lateral spreading [55], overturning [38], creep [56], rotational landslides [57], translational landslides [58], and rockfall [53]. A rock mass moving on the slope surface is subject to three types of movements, which are free fall, rolling, and bouncing (Figure 1). These movements depend on the inclination angle of the slope [59]. The main feature of rockfalls from rock landslides is that rock masses have fall, roll, and bounce movements differently from the continuous flow movement [60]. In rolling rocks, the rolling speed is the least since the energy loss due to friction is maximum. On the other hand, since the friction force is low in the rocks exposed to the free fall movement, the falling speed is high.

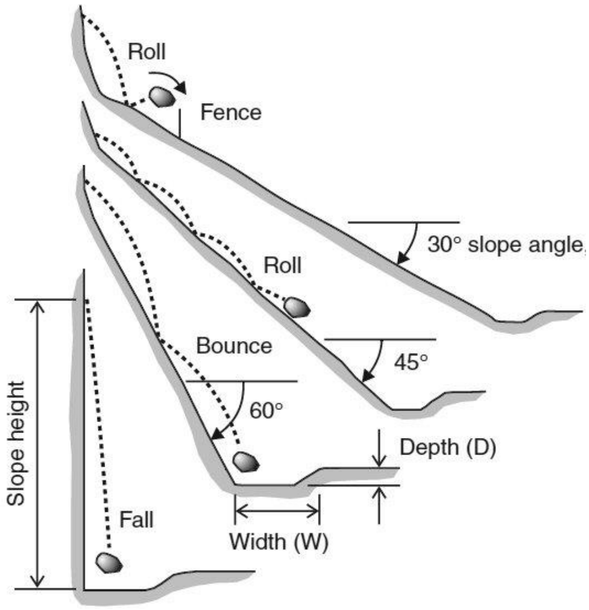

Figure 1. Rockfall travel modes [61]

In rockfall analysis, the point where the rock block begins to fall, the volume and weight of the rock block, the slope inclination, and the vegetation on the slope should be specified. After that, the characteristics such as fall type of rock, the point at which it starts to move, the paths it follows, the bounce height, the movement speed, and the energy it releases should be determined [62], [63]. The specifying of all these factors is quite difficult due to the natural and spontaneous formation of rockfalls and requires a detailed investigation. As a result of the investigations and analyses, it decides the protection method to be taken against the hazard of rockfall. The movement mechanism of falling rock is shown in Figure 2.

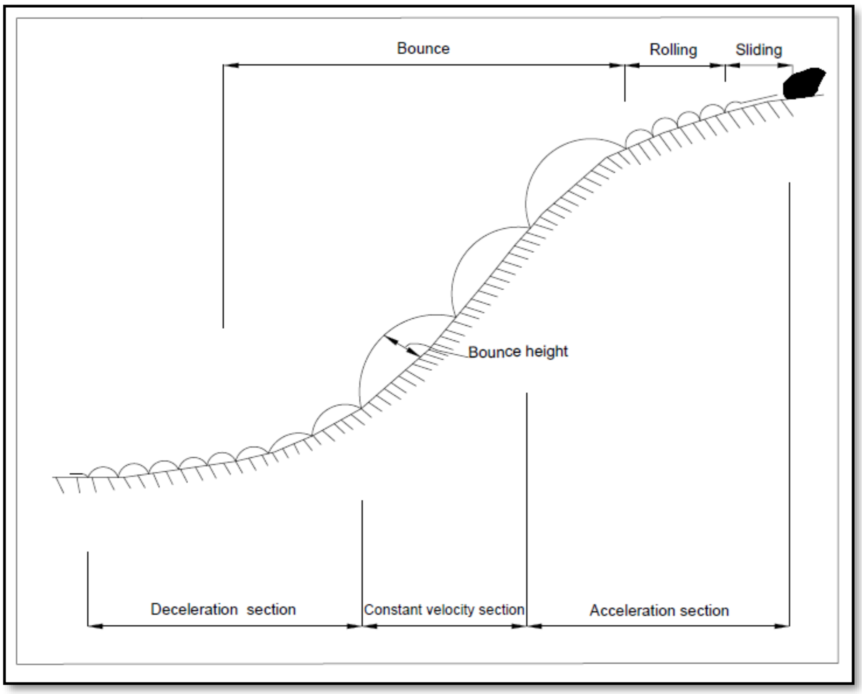

Figure 2. The mechanism of motion of a falling rock [64]

In the event of a rock fall, the velocity of a rolling and bouncing rock is calculated by the following equations.

$$V = \alpha\sqrt{2 \cdot g \cdot H} \tag{1}$$
$$\alpha = \sqrt{1 - (\mu/\tan\theta)} \tag{2}$$

where, V: the velocity of a rolling and bouncing rock (m/s), α: reduction factor, g: acceleration of gravity (m/s^2), H: fall height (m), μ: equivalent friction coefficient and θ: inclination angle of the slope from the horizontal in degree.

The kinetic energy of the rock (E) is the sum of the velocity energy (E_v) and the rolling energy (E_r) and it is calculated by the following equations.

$$E = E_v + E_r \tag{3}$$
$$E_v = 0.5 \cdot m \cdot V^2 \tag{4}$$
$$E_r = \beta \cdot E_v \tag{5}$$

where, E, E_v, and E_r are kinetic, velocity, and rolling energies (J), respectively, m: mass of the rock (kg), V: the velocity of the rock (m/s), β: ratio of rolling energy (~0.10)

When the above equations are re-arranged, the kinetic energy of the falling rock is calculated by using Eq. 6, since W is weight of the rock. The value of rolling energy ratio (β) is generally in the range of 0.1 to 0.4, and 0.1 shall be used most frequently for design calculations [65]. The β is generally taken as ~0.1 and must satisfy the requirement given in Eq. 7.

$$E = (1 + \beta) \cdot (1 - \mu/\tan\theta) \cdot W \cdot H \tag{6}$$
$$(1 + \beta) \cdot (1 - \mu/\tan\theta) \leq 1 \tag{7}$$

While designing the rockfall protection structures, they should have features such as functionality, economy, safety, and structural integrity. For a functional wall design, the wall height should be higher than the bounce height of the falling rock at the place where the wall will be constructed. In the structural design stage, the structural integrity of the wall should be designed depending on the energy (magnitude and distribution on the wall) that dissipates during the collision. A rigorous field study is required for both cases because an efficient protection structure can be designed only in this way. In this case study, passive prevention systems against rockfalls were considered to construct a structure that has all design criteria. Passive prevention systems can be defined as systems in which the movement of large rock blocks is allowed in their falling paths, and the rock blocks are stopped at the most appropriate point [66].

3. REGIONAL FEATURES OF THE STUDY AREA

3.1. Geographical Location

The town of Dereköy is 130 km away from Konya city center and 7 km from Bozkır district. It is located at the latitude of 37.20244083 and longitude of 32.10548401. In the north of the town of Dereköy, there are Akören and Çumra districts, the Güneysınır district in the east, the Hadim district in the south and Ahırlı district in the west (Figure 3). The climate, vegetation, and social and economic lives of the town, which is located on the slopes of the Taurus Mountains overlooking the Central Anatolia Region, are shaped by the influence of these rugged geographical conditions. The topography of Dereköy, which is a mountainous area, does not contain plateau areas, but there are notched and bottom valleys. It is on the edge of Çarşamba River as a settlement area, which is a transition area between the continental and the Mediterranean climate. The average height above the sea level is 1162 meters. Agriculture and livestock constitute the economy in the study area.

3.2. Climate

In the Bozkır district and its surroundings, the Mediterranean Mountain climate, which is the type of transition between the sea and the continental climate, is dominant. However, the typical Central Anatolian climate dominates in Bozkır due to the Taurus Mountains. Summers are hot and dry; winters are cold and snowy. Bozkır district and its surroundings are generally not rich in terms of soil. Major soil forms found in the Bozkır district are brown forest lands, brown and red-colored soils, and alluvial and colluvial soils. In these soils, juniper, fir, cedar, cranberry, boxwood, and oak forests; shrubbery and steppe species are the vegetation.

The average temperature of the town is the lowest value at -1.0°C in February and -0.9°C in January. The highest temperature values were observed in the summer months. The average temperature of 17.9°C in June reaches a maximum of 21°C in July. The lowest temperature in the town is observed at -13.2°C in January. The monthly lowest temperatures are negative in November but rise above 0°C from April. The highest monthly minimum temperature value was recorded in July at 9.8°C. The annual average of the minimum temperature values of the district is -13.6°C (Figure 4).

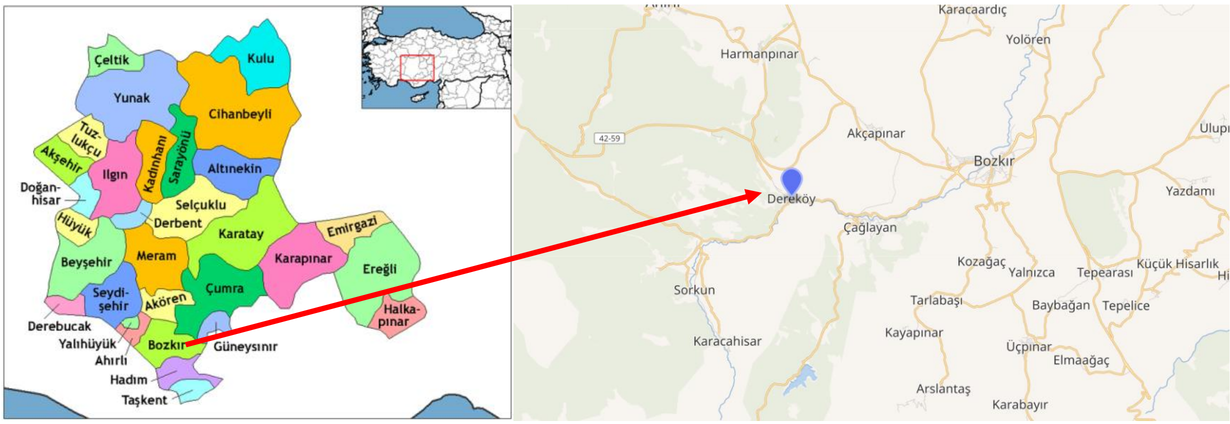

Figure 3. Geographical location of Dereköy town in Konya, Turkey

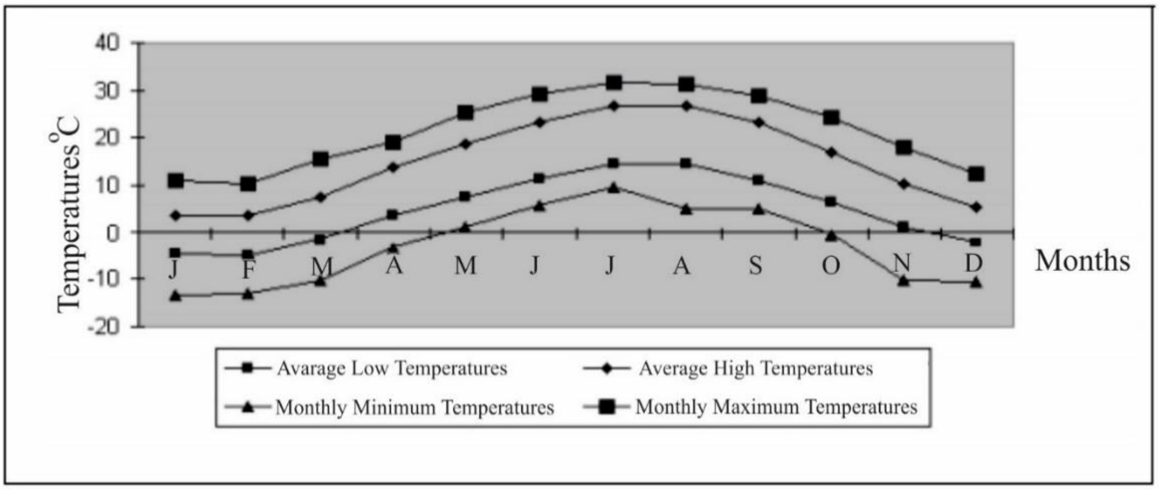

Figure 4. Temperature distribution of the Dereköy town per months [67]

The number of days with frost in Bozkır is an average of 96.4 days per year. Frost events start in October in the district and continue until May. The minimum and the maximum number of days of frost events is 0.4 days in May and 23.8 days in January, respectively. In the district, frost events were observed for nine months of the year.

The average annual relative humidity rate is 58.1% in Dereköy, a moderately humid region. The reason for this is that the winds blowing from the southwest have the feature of blowing over the Taurus Mountains. The highest relative humidity in Dereköy is 70.6% in December. The lowest humidity is 45.7% in August.

Dereköy shows the characteristics of the distorted Mediterranean climate, summer drought, and winter precipitation dominate. In the winter, precipitation is mostly snow. However, with the impact of the Mediterranean climate, precipitation is in the form of slush.

The average annual precipitation in Bozkır is 627.9 mm. The most monthly precipitation is observed in December. The amount of rainfall, which is 117.4 mm in December, decreases to 72.2 mm in February. The precipitation is continuously decreasing from 71.4 mm in March to 4.9 mm in August. After this time, the precipitation started to increase again and reached its highest level in December.

The most precipitation occurred in winter with 291.3 mm in Dereköy. The amount of precipitation falling in the winter months is 46.3% of the total annual precipitation. The second rainy season is in the spring season, and the amount of rainfall in this season is 163.9 mm, which corresponds to 25.8% of the annual precipitation. The amount of precipitation falls in the autumn is 137.8 mm and 39.9 mm in summer (Table 1).

The highest wind velocity was 37.6 m/sec in March, and the lowest was 17.1 m/s in August. The prevailing wind in this region is the southwest-directed wind, with an annual average value of 28.31 m/s. In terms of vegetation, macaque and sparse forests are found in the study area.

3.3. Socio-economic Life

The town's economy has long been based on agriculture and livestock since the town is located on a mountainous and rough terrain. The people of the town generally earn their livelihood by cultivating a small amount of land, gardening on the water's edges, and animal husbandry.

3.4. General Information on Construction Site

Geological forms from the oldest to the youngest in the study area can be listed as limestones, ophiolites, phyllites, conglomerates, and alluvium (Figure 5). The rock blocks observed on the slopes of the study area consist of limestone. The topography of this area has about 27-35 degrees of slope inclination. Rock blocks have cracks, joints, and clastic. The diameter of the limestone blocks varies between 1 m and 4 m. These rock blocks are generally decomposed as a result of atmospheric conditions. The crack systems in the rocks have grown as a result of rain and snow waters leaking into cracks. As a result, it was observed that some rock blocks were separated from the rock bottom and were suspended, but the remaining part fell. The falling blocks were spread in the forest area at a distance of about 200-250 m from the nearby settlements and remained in balance on the slope. In addition, the rock blocks falling apart from the upper elevations trigger the movement of the rocks in the forest. The distance of the rock blocks to the houses changes between 15 m to 250 m. The geographical borders of the area that may be affected by the rockfall are shown in Figure 6. There are 150 houses under rockfall risk in this area. Vegetation, consisting of sparse trees, does not completely stop the falling rock blocks on the inclined terrain.

During the field studies, it was observed that the rock fragments that were broken off from the bedrock were standing freely or leaning against the trees. Falling rock blocks occasionally threaten houses in the neighborhood. Due to the geological, topographic, and climatic conditions of the region, the falling rock blocks are very dangerous in terms of life and property safety. A picture of the rock masses in the study area is given in Figure 6.

Table 1. Amount of precipitation in Dereköy in each season [67]

Amount of precipitation	Seasons			
	Spring	Summer	Autumn	Winter
mm	163.9	39.9	137.8	291.3
%	25.8	6.2	21.7	46.3

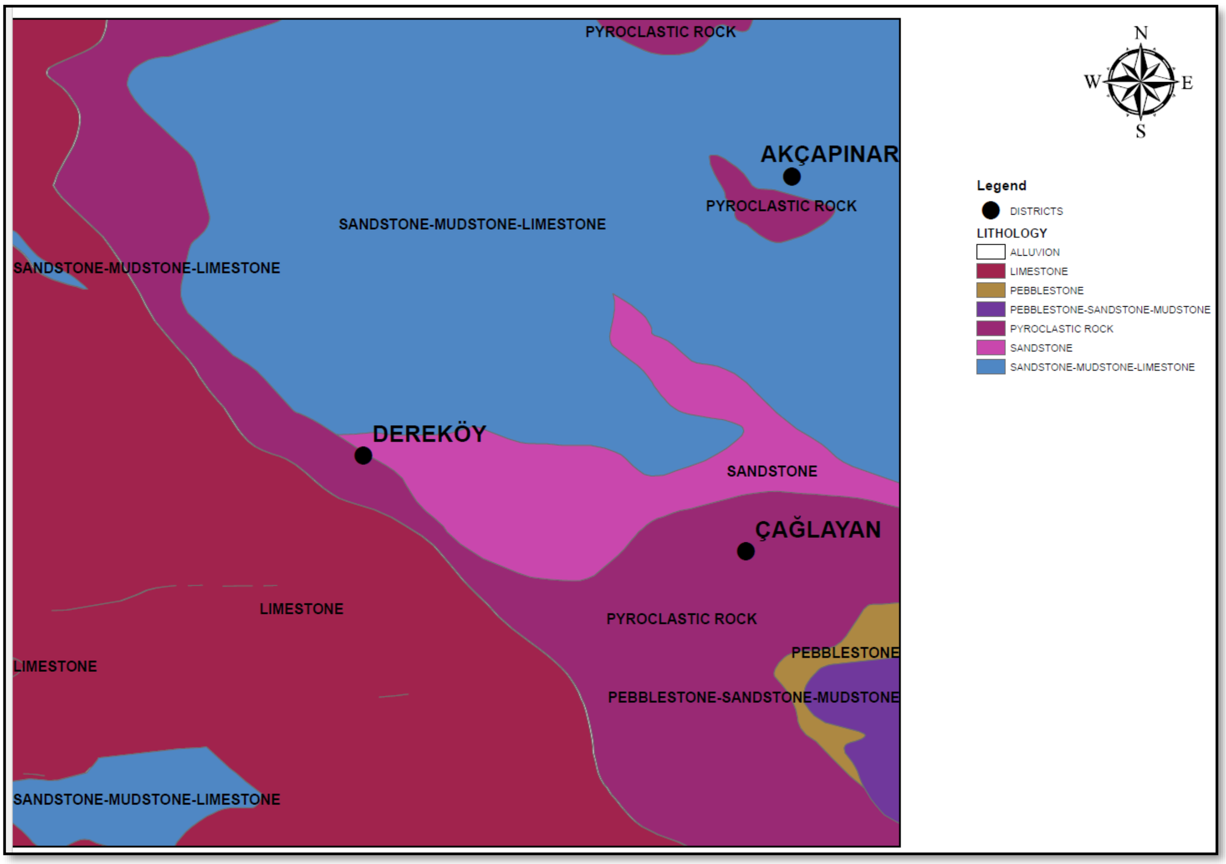

Figure 5. Geological map of construction site [68]

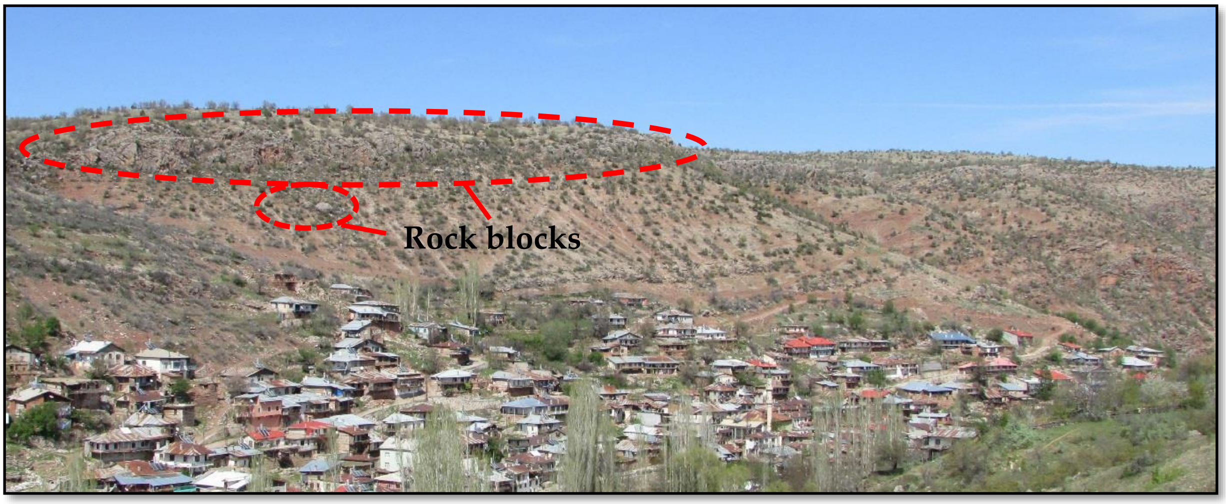

Figure 6. The geographical borders of the study area and rock blocks on slope

4. ROCK FALL ANALYSIS RESULTS

As a first step, the land topography of the region at risk of rockfall was determined. In the study area, measurements were made by using the CORS (Cross-Origin Resource Sharing) device, and the current situation of the land was determined. A detailed mapping study was carried out (Figure 7). The possible blocks to fall are examined and dimensioned on this map. It is made ready for use in the analysis by taking the cross-sections from different places.

The simulation of the cliff was performed in RocScience's analysis package program RocFall [69]. RocFall is a computer software program designed to statistically assess the risk caused by falling rocks from the cliff face [70]. The program determines the energy, velocity, and bounce height of falling rock blocks for the entire slope along the location of rock endpoints. It can also assist in the estimation of remedial measures [71]. After the topography of the study area was determined, analyses were made in cross-sections of A-A′, B-B′, C-C′, D-D′, E-E′, and G-G′ (Figure 7) by using the Rocfall package program. However, the most crucial cross section is D-D′ since the total kinetic energy, bounce height, and translational velocity of rocks are maximum in this cross-section. Details of the D-D′ cross-section are given in Figure 8. According to this, lots of rockfall scenarios of the rounded rock masses were determined. Then, the energies, bounce heights, and velocities of the rock masses for each cross-section were determined.

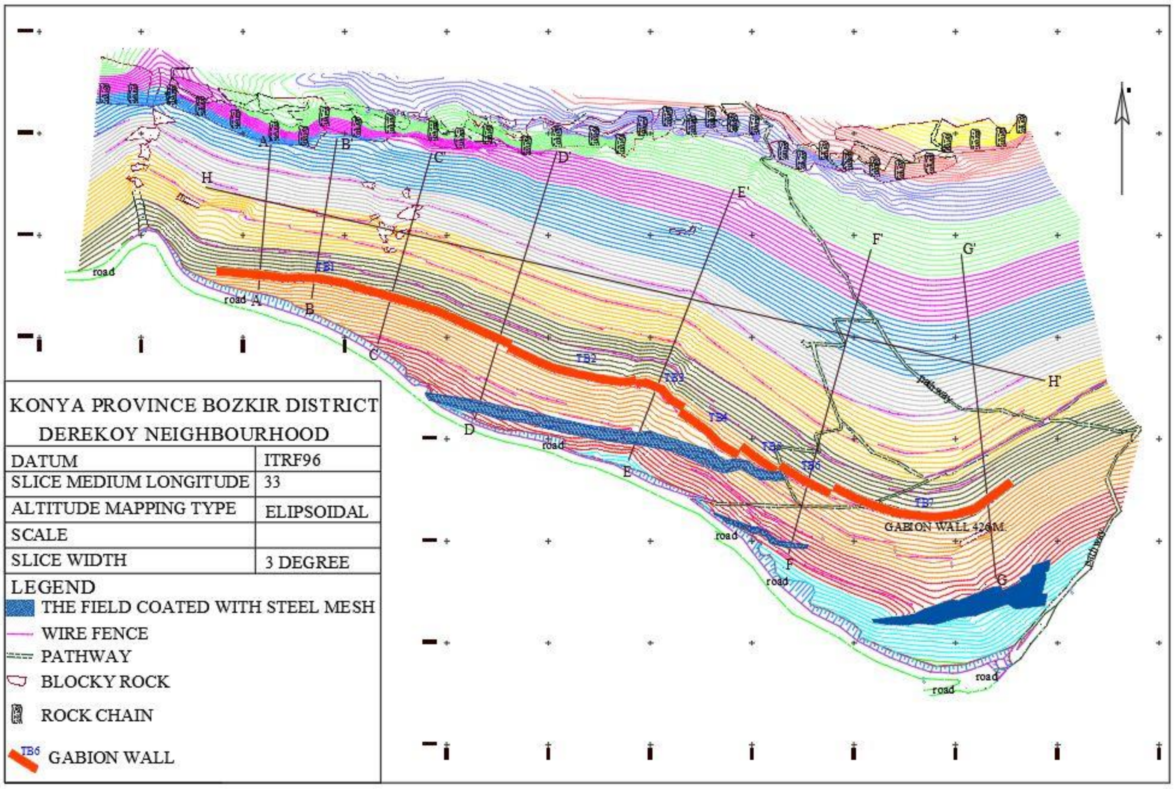

Figure 7. Mapping study with the CORS device and cross sections at different locations

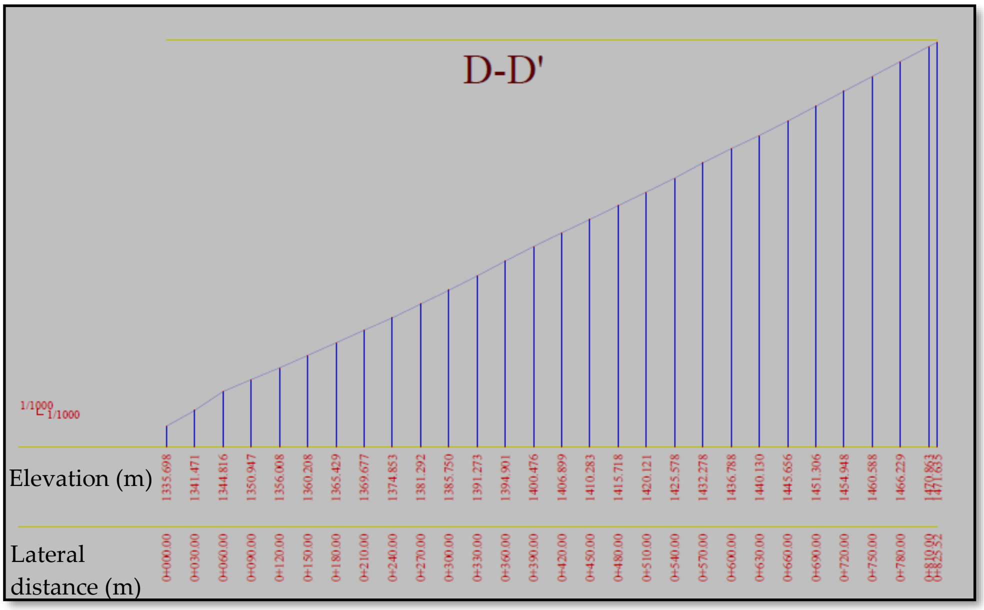

Figure 8. Cross-section of D-D′ axis

With the help of the Rockfall package program, simulations of the falling rocks that are likely to fall on the surface of the slope were performed. The Rockfall analyses were performed separately in situations with and without constructing barriers. In case of the absence of a barrier, the rocks will damage the houses.

In the field study carried out in Dereköy district, it is appropriate to build a rock-holder barrier on the slopes close to the houses due to the steep slope of the land structure and the fact that the rock blocks are spread all over the land. As a result of the technical analysis, the type, height, location, and position of the barrier were determined.

According to the analysis results, it is foreseen that the masses of 2500 ± 500 kg will pass through vegetation and trees. In this situation, friction parameters are considered for hard rock (R4) according to rock strength classification. To determine this, core samples were taken from various of the rocks, and then unconfined compressive [72] and splitting tensile strength [73] tests were performed. An average unconfined compressive strength (UCS) value of rocks were 65.3 MPa and they were classified as hard rock (R4) since it was between 50 and 100 MPa [74]. In addition, splitting tensile strength (STS) of rock was 20.4 MPa. Internal friction angle and cohesion of rock is 30° and 18.3 MPa, respectively. They were obtained from the characteristics of failure envelope (Figure 9) which tangent to Mohr circles of UCS and STS tests [75]. Other parameters used in the analysis are given in Table 2. Number of throws is 50 based on the existing literature [76], [77]. Another factor is the selection of a surface model for the slope. In the RocFall software, surface models and their R_n (coefficient of normal restitution) and R_t (coefficient of tangential restitution) values are defined. However, a new surface model was created for the case study area. In the analysis, the slope surface is selected as "Talus Cover", R_n and R_t values are defined automatically for the surface. The friction angle was calculated using the R_t value. In the general structure of the slope, no standard deviation was predicted in the coordinate points used in determining the cross-sectional properties. The study was specifically designed to determine the energy-damping capacity of the barrier. The coefficient of restitution (CoR) is an important parameter for obtaining the loss of energy in rockfall simulation at every impact along the slope. The values can be measured through in situ tests [78], [79], [80], [81], [82], back analysis [83], and laboratory studies [84], [85], [86], [87]. Chau et al. [88] had experimentally determined the restitution coefficients for boulders impacting on rock slopes under various impacting conditions. Azzoni et al. [83] have determined that the value of CoR ranges from 0.51 to 0.92 for the rock slopes.

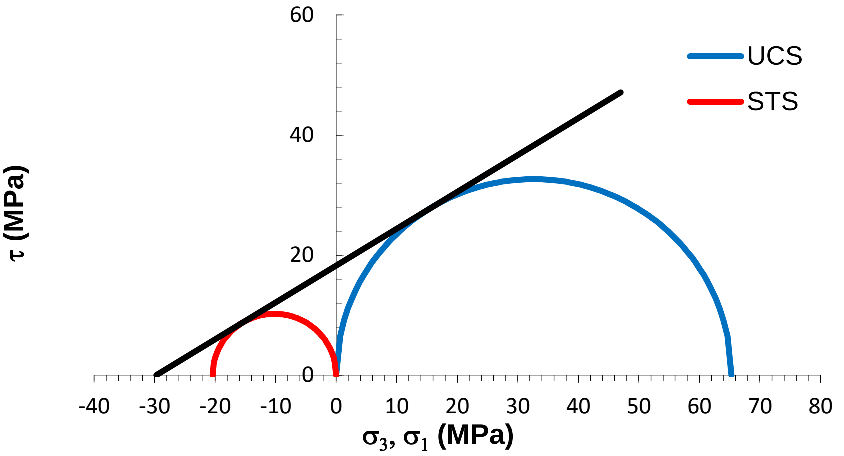

Figure 9. UCS and STS test results and failure envelope of rock samples

Table 2. The parameters used in the Rockfall analysis

Parameters	Value
Minimum velocity cut-off (m/s)	0.1
Friction angle (degrees)	30
Cohesion (MPa)	18.3
Number of throws	50
Coefficient of normal restitution (R_n)	0.32 ± 0.04
Coefficient of tangential restitution (R_t)	0.82 ± 0.04
Slope roughness	0
Horizontal velocity (m/s)	0.1
Sampling interval	50

In the analysis, rock blocks of 2500±500 kg mass start to move with the first velocity of 0.00 m/s from the top points of the slope. Then, rock blocks roll over the slope surface and fall to the houses. Unit weights of rock masses were not determined experimentally and are assumed to be between 15.0-18.0 kN/m^3 [89], [90], concerning the possible cracks in the rock masses. Shear strength of rock was hard rock (R4) class. It is thought that the rock blocks of approximately 1.3-1.6 m^3 having a fractured and fragmented structure may fall. The possible rockfall routes that may occur during the analysis of various rockfall scenarios are shown in Figure 10. Accordingly, the location of the barrier is shown in Figure 10. Total kinetic energy, bounce height, and translational velocity of falling rock masses were considered for the type of barrier to be used in the investigations using the RocFall program. Similar results were obtained for each cross-section.

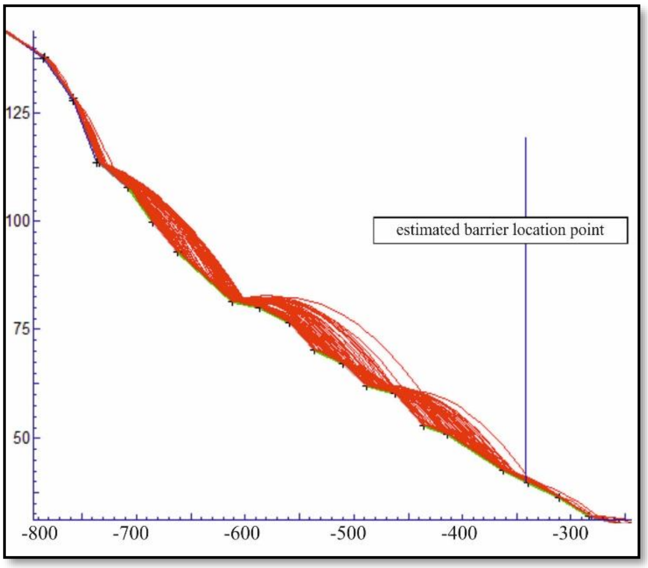

Figure 10. Possible rock fall routes as a result of various rock fall scenarios (for D-D′ cross-section)

4.1. The Kinematic Properties of Rocks During Collision

In the analysis, it was anticipated that 2500±500 kg of rocks could fall. If these rocks are allowed to free-fall from an average height of 300 meters, the total energy in the frictionless environment will be 6250 kJ. The total kinetic energies of the rocks on the route to be followed during the fall are given graphically for each point separately. In addition, the maximum energy at the point where the rocks hit the houses is 500 kJ (Figure 11). If a single barrier is used to prevent rock falls, the optimum point where the barrier can be placed is 150 m from the slope toe. Figure 12 shows the location of the gabion wall on the satellite image. Since the route of gabion wall was not on a straight line, the wall was divided into regular pieces (TB1 to TB7) and thus the cost is calculated easily. It is analyzed that if the rock masses roll on the surface by moving about 300 meters from the vertical distance, they will bump by the energy of about 500 kJ on the barrier. Due to vegetation and inclination on the slope surface, the energy is damped and reduced from 6250 kJ to 500 kJ.

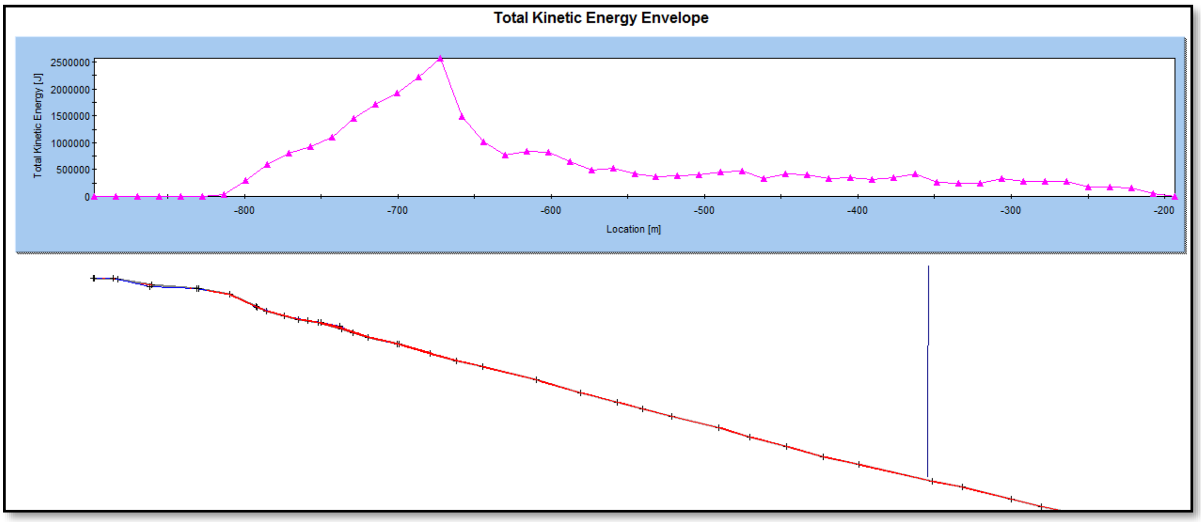

Figure 11. The total kinetic energies of the rocks on the fall route (for D-D′ cross-section)

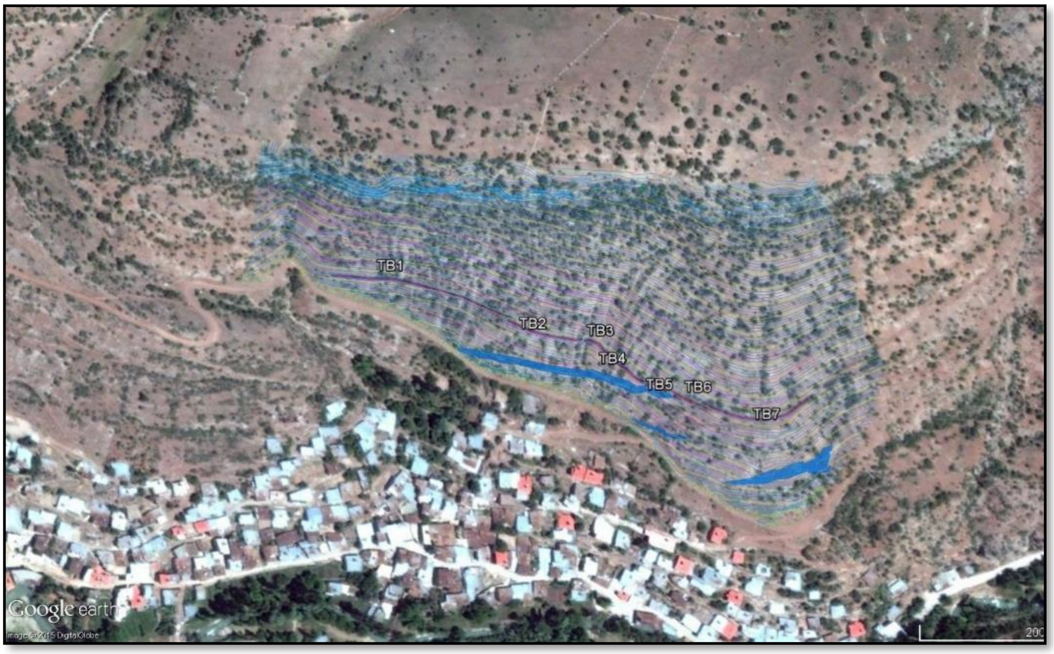

Figure 12. Location of the gabion wall on the satellite image

Considering the barrier location, the rolling rocks should not cross over the barrier. This situation can be clarified by the height of the bounce at the point where the rocks will bump into the barrier. The bounce heights of the rocks along the slope are given in Figure 13 and it was observed that the rocks would bounce to an average of 0.5-1.0 meters during the collision.

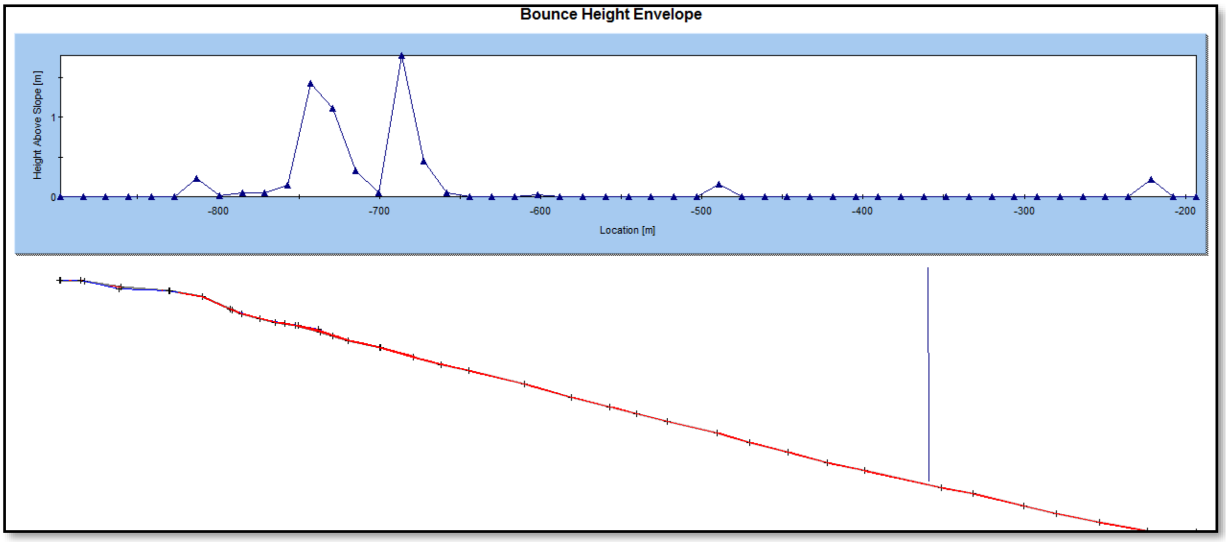

Figure 13. The bounce heights of the rocks along the slope (for D-D′ cross-section)

Another important point in the barrier design is the velocity of the rocks at the point where they bump the barrier. The rocks that will bump the barrier with speeds above 30 m/s can penetrate the barriers at that point. In the analyses, it was determined that the velocity of the rocks at the point of collision would be around 15.0 m/s (Figure 14).

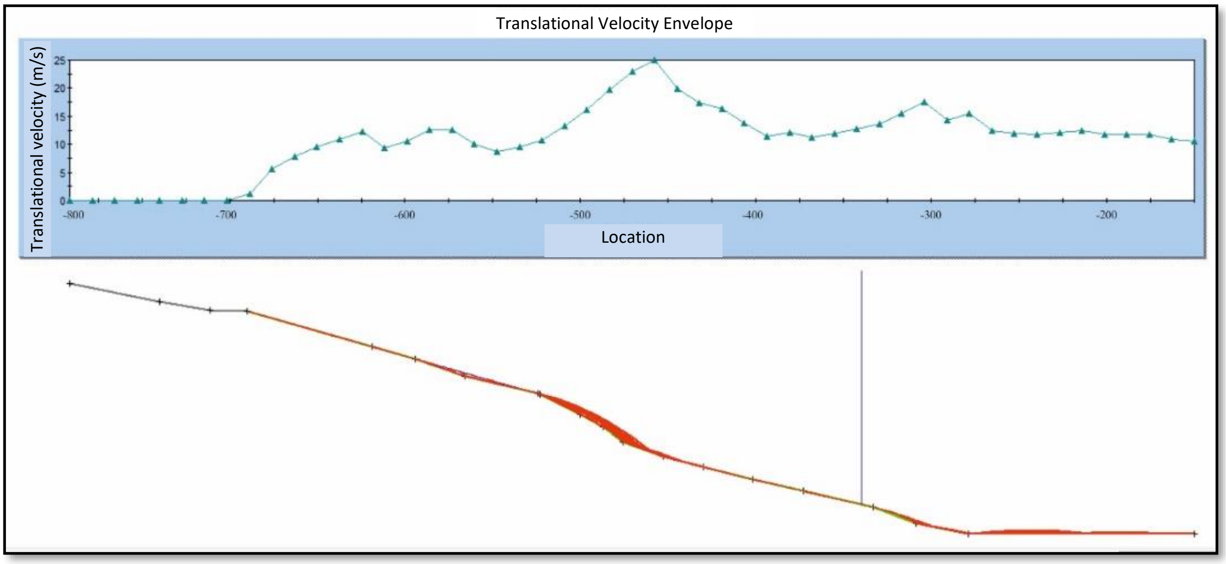

Figure 14. Translational velocity of the rocks along the slope (for D-D′ cross-section)

5. COST-BENEFIT AND RISK ANALYSES OF ALTERNATIVE ROCK FALL PROTECTION METHODS

In the research area, a gabion wall was constructed to prevent rock falls. Before this decision, different methods to prevent rockfalls were evaluated. Considering the construction stages, project duration, occupational health and safety, and cost-benefit analyses for these methods, a short evaluation is given below.

The surface coating with steel mesh, which is one of the preventive structures against rock falls, is not enough due to the large dimensions of rocks. This method needs a system reinforced with steel ropes having high energy-absorbing capacity. This system needs 2.7-mm-thickness steel wires, which have a mesh of 8mmx10mm aperture sizes. In addition, the system must be reinforced vertically with 10mm steel ropes in thickness. The cost of such a system is 193000 $. In addition, the feasibility of this system is not proper for workers’ safety and application difficulties. Covering a large area with steel mesh takes a long time, but completion of the work is urgent for safety purposes. In large areas, it can be a solution to place energy-dissipating barriers in front of the falling rocks by the falling routes and energies at that point. However, the cost of the 420 m long energy-dissipating barrier, having 500kJ energy damping capacity, was 467000 $ in 2015. In addition, the import of energy-dissipating barriers is also difficult to provide. On the other hand, when the energy-dissipating barriers are subject to rockfall, the energy-dissipating devices must be replaced because they become unusable. This increases the maintenance costs of this system.

According to the prices in 2015, the cost of moving 150 houses to 100 m^2 detached houses with gardens is only 3.89 million $ in the system of semi-state semi-citizen contribution. When this amount is contributed financially by the citizen, the amount is twice. In cases where there is no suitable public land to move, the total cost increases 6-7 times when the cost of expropriation and infrastructure costs for new settlements are included.

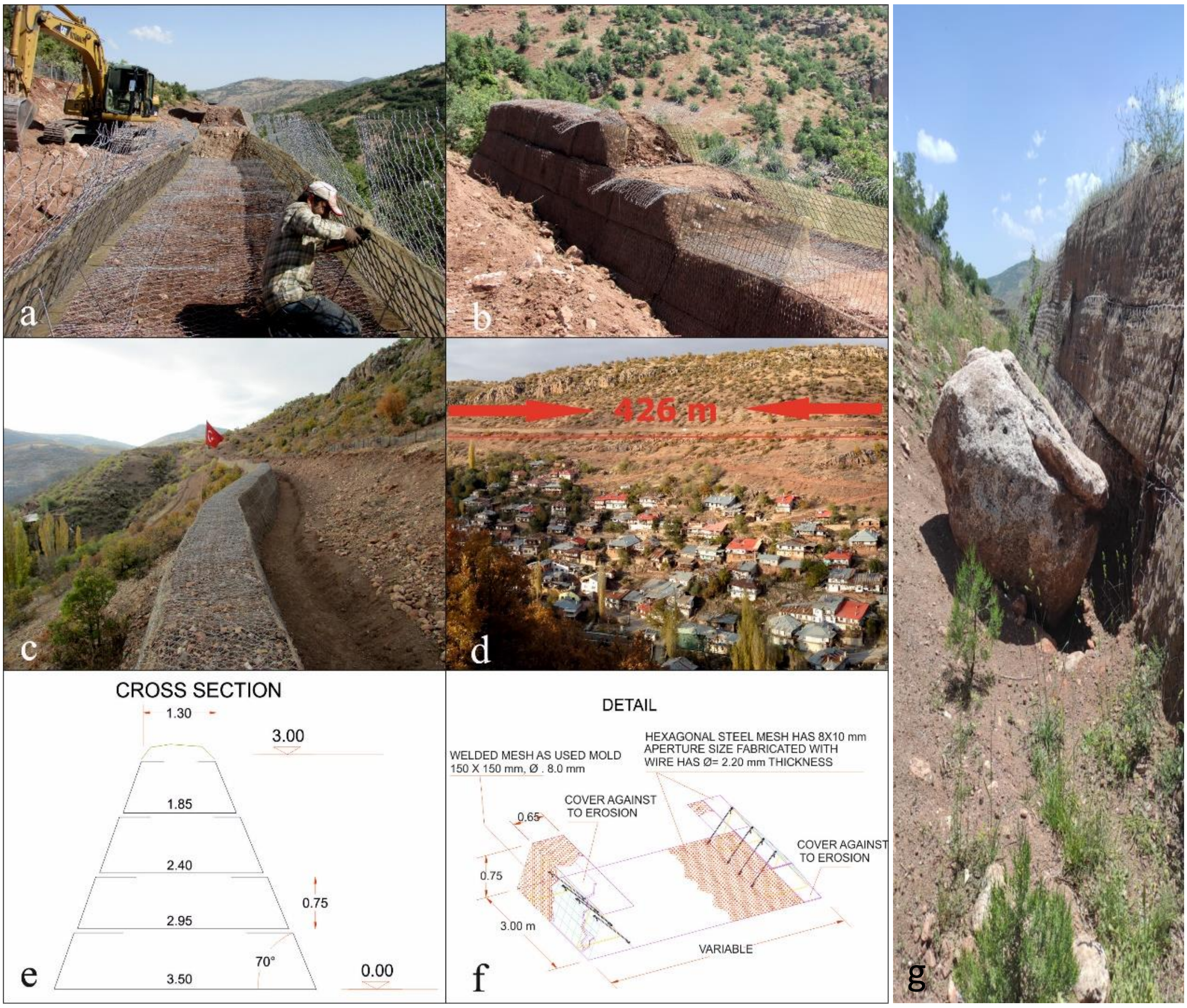

Figure 15. Stages of gabion wall construction: a) building-up gabion wire cage, b) box filled with soil, c) construction of gabion wall, d) general view of construction site, e) the cross section of gabion wall, f) detail of each panel, and g) the demage of fallen rock on D-D′ cross-section

The steel wire used for constructing the gabion wall has a thickness of 2.2 mm with a galvanizing coat of 0.8 mm to protect it from rusting. Finally, it has a PVC coating on the top surface for the protection of galvanization. The land soil was suitable for the filling material of the gabion wall. The stones, greater than 15 cm in diameter, were not included in the gabion cage. After filling the cage, the soil was compacted enough. The total cost of a 3 m high gabion wall along a 426 m line is 110000 $. For this reason, it was thought that this method would be appropriate in the study area and it was constructed (Figure 15). It has been observed that the gabion wall has a very high resistance to falling rocks throughout its service life. Periodic controls (twice a year) conducted in the region over the years have determined that there have been rock falls. The falling rock (approximately 1.5m^3) at the critical D-D′ cross-section has caused local deformation on the wall but the wall satisfies the general stability criteria (Figure 15g).

6. CONCLUSION

The rocks in the study area are scattered at both tops of the slope and slope surface. Therefore, it is concluded that the construction of the rockfall preventive structure should be close to the houses. As a result of the analyses, it was seen that the total energies of the rocks will be 500 kJ, their bounce height is 1.0 m and their velocity will be 15.0 m/s at the place where the preventive structure of the rockfall will be built.

In terms of catastrophic risks, moving houses is the safest and most secure method to move away from danger. However, moving 150 houses from the region was not considered because of socio-economically reasons. Moving of homes in areas exposed to disasters in Turkey, even in cases where their moving operations into detached houses with gardens were generally unsuccessful. Since the citizens living in the countryside were engaged in agriculture and animal husbandry, they could not adapt to the places where the dwellings were moved and returned to their homes located in areas subject to disasters. In the following years, the people living in these houses, which have passed through to the next generation by inheritance, have entered the risk in terms of security of life and property. Another problem in the moving process is that all the houses in the area are not moved. That is, the local people were away from their relatives and neighbors caused sociological problems because the houses in the disaster-affected area are moved and the remaining houses outside the region exposed to the disaster remain in the settlement area. One of the other alternatives is moving the local people to housing estate because the cost of moving is lower compared to individual houses. However, moving the houses was unsuccessful even if local people were moved to housing estates close to the city center. Here, the livelihoods of local people and their ability to work should be taken into consideration.

When the measures that can be applied against rockfalls are compared in terms of cost and applicability, it is understood that the most reasonable and appropriate solution is the construction of the gabion wall. In addition, it is a great advantage that the gabion wall does not require maintenance costs.

DECLARATION OF ETHICAL STANDARDS

The authors declare that they comply with all ethical standards.

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

Author 1: Conceptualization, Formal analysis, Investigation, Methodology, Resources, Software, Writing – original draft, **Author 2:** Formal analysis, Investigation, Resources, Validation, Visualization, Writing – original draft, Writing – review & editing, **Author 3:** Methodology, Supervision, Validation, Writing – review & editing

DECLARATION OF COMPETING INTEREST

The authors have no competing interests to declare that are relevant to the content of this article.

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DATA AVAIBILITY

All data generated or analyzed during this study are included in this published article.

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