Yerbilimleri, 2017, 38 (2), 161-178
Hacettepe Üniversitesi Yerbilimleri Uygulama ve Araştırma Merkezi Bülteni
Bulletin of the Earth Sciences Application and Research Centre of Hacettepe University

Assessment of Rockfall Hazard on Steep Slopes: Ermenek (Karaman, Turkey)

Dik Yamaçlardaki Kaya Düşme Tehlikesinin Değerlendirilmesi: Ermenek (Karaman, Turkiye)

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Geliş *(received)* : 09 Şubat (*February*) 2017
Kabul *(accepted)* : 17 Mayıs (*May*) 2017

ABSTRACT
Ermenek is a extraordinary settlement area due to its topographical features in Karaman (Turkey). The city is located in the northern side of the steep cliffs, which are formed of jointed limestone that abruptly increases from 1250 m to 1850 m. Moreover, these cliffs, having a slope dip of nearly 90°, are the main rockfall source areas due to their lithological characteristics, climatic effects and the engineering properties of rock units. Up to now, depending on the rockfall event, nearly 500 residences have been severely damaged, and the loss of life has occurred in Ermenek. The rockfall phenomenon is initiated by discontinuities, lithological changes, weathering and the freeze-thaw process in the study area. In this study, extensive fieldwork including the determination of locations and dimensions of hanging, detached and fallen blocks; a detailed discontinuity survey; and the description of geological, morphological and topographical characteristics was performed. Additionally, rockfall hazard has been evaluated by two-dimensional rockfall analysis involving 10 profiles. While these profiles were determined, the locations where the most of the fallen blocks are observed are selected in the field study. During the rockfall analysis, run-out distance, bounce height, kinetic energy and the velocities of various sizes of blocks for each profile were determined through the use of RocFall v4.0 software. The results obtained from the rockfall analysis were used to map the areas of possible rockfall hazard zones, and rockfall source areas were interpreted.
According to the rockfall analysis, field study and laboratory testing, protective and preventive recommendations can be suggested for the areas threatened by rockfall. However, the most widely known remedial measures in literature, such as trenches, retaining walls (barriers), wire mesh, cable/stretching nets and rock bolting, etc., are not sufficient in the study area due to its topographical, atmospheric and lithological features. For these reasons, hanging blocks in the reachable locations can be removed, the total evacuation of the danger zone may applied, and then taking safety measures in this area to make it safer for the residents.

Keywords: Ermenek, hazard, limestone, rockfall, zonation map.

ÖZ
Ermenek, topoğrafik özellikleri nedeniyle Karaman (Turkiye) ili sınırları içerisindeki en ilginç yerleşim alanıdır. Yerleşim yeri, 1250 m'den 1850 m'ye yükselen eklemli kireçtaşlarından oluşan oldukça dik, sarp kayalıkların kuzey tarafında yer almaktadır. Bunun yanı sıra, yaklaşık 90° eğime sahip olan bu şevler, kaya birimlerin litolojik ve mühendislik özellikleri ile iklim etkisi nedeniyle kaya düşmesi kaynak alanlarıdır. Şimdiye kadar, Ermenek'te kaya düşmesi nedeni ile yaklaşık 500 konut ağır hasar görmüş ve can kaybı ile sonuçlanan kaya düşmeleri meydana gelmiştir. Çalışma alanındaki kaya düşmelerine neden olan etmenler; süreksizlikler, litolojik değişiklikler, iklim ve donma-çözülme süreci olarak tanımlanabilir. Bu çalışmada; yürütülen yoğun ve detaylı süreksizlik analizleri ile asılı, ayrılmış ve düşmüş blokların yerleri ve boyutları saptanmış, ayrıca jeolojik, morfolojik ve topoğrafik özellikleri belirlenmiştir. Buna ek olarak, kaya düşmesi tehlikesi, 10 profilde iki boyutlu kaya düşmesi analizleri ile değerlendirilmiştir. Kaya düşmesi analizi sırasında, her bir profil için çeşitli boyutlarda blokların kaçma mesafesi, sıçrama yüksekliği, kinetik enerji ve hızları RocFall v4.0 paket programı kullanılarak belirlenmiştir. Kaya düşmesi analizinden elde edilen sonuçlar, muhtemel kaya düşme tehlike bölgelesi alanlarını belirlemek için kullanılmış ve kaya düşmesi kaynak alanları yorumlanmıştır.

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Yapılan kaya düşmesi analizleri, saha çalışmaları ve laboratuar deney sonuçlarına göre, kaya düşmesi tehdidi altında olan alanlar için koruyucu ve önleyici yöntemler önerilebilir. Ancak, literatürdeki en yaygın yöntemler olan; hendekler, istinat duvarları, tel örgüler, gerdirme ağlar, kaya saplamaları vb., çalışma alanının topoğrafik, atmosferik ve litolojik özellikleri nedeniyle yetersiz kalmaktadır. Bu nedenle, bölgede yaşayan sakinlerin daha güvenli olabilmeleri amacıyla, öncelikle tehlike bölgeleri tahliye edilmeli ve sonrasında, güvenlik önlemleri alınarak, erişilebilen yerlerde asılı bloklar temizlenmelidir.

Anahtar Kelimeler: *Ermenek, tehlike, kireçtaşı, kaya düşmesi, zon haritası.*

INTRODUCTION

Rockfall is a fast movement of blocks that are detached from the bedrock along discontinuities. The blocks slide, roll or fall vertically down the slopes, bouncing and flying along trajectories (Varnes, 1978; Whalley 1984; Dorren 2003). Due to their high speed and energy, rockfalls can be admissible as a substantially destructive mass movement resulting in significant property damage and loss of life. This movement is mainly controlled by the geological conditions of the rock units, climatic influences and the process of weathering. Moreover, discontinuity patterns and the related intersections play an important role in the sizes and shapes of the detached blocks (Perret et al., 2004).

The slope characteristics are significant factors in rockfall events. The normal (R_n) and tangential (R_t) components of the coefficient of restitution are related to the slope characteristics that control the behavior of the falling blocks, and they are the most crucial input parameters in rockfall analysis (Chau et al., 1996). Both components of coefficient of restitution are related to the material that covers the surface, vegetation, surface roughness, and the radius of the falling rocks (Dorren et al., 2004). The coefficient of restitution with normal and tangential components can be determined by the field tests and back-analysis. Although researchers have revealed various techniques with which to determine the coefficient of restitution, these parameters should be identified individually for each side because of the different geometrical features and mechanical properties of the slopes (Pfeiffer and Bowen 1989; Evans and Hungr 1993; Robotham et al., 1995; Agliardi and Crosta 2003; Dorren et. al, 2004; Ulusay et al., 2006; Topal et al., 2007; Topal et al., 2012, Buzzi et al., 2012, Bourrier et al., 2012). However, slope inclination and slope properties also affect the run-out distances of the falling blocks (Okura et al., 2000). The slope surface of hard rock that is free from vegetation cover is more dangerous than the surface covered by vegetation or talus material because of the fact that it does not hinder the movement of falling blocks.

To simulate the fall of a block down a slope and thereby compute rockfall trajectories, various two-dimensional (2-D) three-dimensional (3-D) and 2-D/3-D DDA (Discontinuous Deformation Analysis) software have been developed and tested over the past few years, and many studies considering rockfall analysis and simulation have been carried out. Additionally, the rockfall susceptibility and hazard maps have been produced using two- and three-dimensional rockfall analysis techniques, considering the maximum travel distance of a falling block. (Bassato et al., 1985; Falcetta, 1985; Bozzolo and Pamini, 1986; Hoek, 1987; Pfeiffer and Bowen, 1989; Chen et al., 1994; Azzoni et al., 1995; Jones et al., 2000; Guzetti et al., 2002, Guzetti et al., 2003; Agliardi and Crosta, 2003; Schweigl et al., 2003; Perret et al., 2004; Taga and Zorlu, 2007; Yilmaz et al., 2008; Tunusluoglu and Zorlu, 2009; Zorlu and Taga, 2009; Binal and Ercanoglu, 2010; Zorlu et. al., 2011; Katz et al., 2011; Topal et al., 2012; Keskin 2013; Duncan, 2014).

In this study, rockfall analysis was performed in the Ermenek district, located on very steep cliffs, considering past recorded phenomena and recently ongoing threats of events (Figure 1). Rockfalls occur very close to residential area and already damaged the houses and unfortunately have been loss of lives. To reveal the rockfall potential of the study area, extensive field work including a detailed discontinuity survey, the determination of location and dimensions of hanging, detached and already fallen blocks, and back analysis was conducted. Two-dimensional rockfall analysis was conducted along 10 selected profiles in order to assess the block trajectories, run-out distance, kinetic energy and bounce height of the blocks, based on field and laboratory test data. Then a rockfall hazard map was produced by means of the results obtained from rockfall analysis, and the areal extension of falling rocks was delineated. When the location, climatic adversities and geological factors of the study area are considered, some

Figure 1. Location map of the study area.
Şekil 1. Çalışma alanının yer bulduru haritası.

remedial measures can be arguable. Besides the unfavorable conditions, possible remedial measures are also suggested for the study area.

GEOLOGICAL SETTINGS

The Ermenek basin is one of the Neogene molasse basins in the Central Taurides, with the orogenic belt segment stretching between the Isparta angle to the west and the Ecemiş Fault to the east (Özgül, 1976; Ilgar and Nemec, 2005). The Ermenek Basin and the adjacent Mut Basin lie between the Cukurova Basin complex to the east and the Antalya Basin complex to the west, and are situated within the central part of the Taurides, an east-west trending orogenic belt that originated through compressive deformation during the initial stage of the closure of the southern branch of the Neo-Tethyan Ocean in the Early Cenozoic (Safak et al., 1997). The basins evolved as extensional grabens related to preexisting fractures. Deposition resumed in the Early Miocene, with the Mut Basin hosting alluvial sedimentation and the Ermenek Basin becoming a large clastic lake. The two basins, which formed as separate intramontane depressions, were then inundated by the sea, end of the Early Miocene and were jointly covered by an extensive, thick succession of late Burdigalian-Serravalian carbonates, including reefal and platform limestones (Ilgar and Nemec, 2005).

The tectonic history of Southern Turkey are evaluated into three major periods: (1) Late Paleozoic to Middle Eocene: formation of the Tethyan orogenic collage; (2) Middle Eocene to Middle Miocene: Tauride orogeny during continued north-south convergence and collision; and the migration of deformation front south of Turkey; (3) Late Miocene to recent: collision of Eurasia with the Arabian Plate and start of the Neotectonic Regime (Bassant et al., 2005). Due to this complex tectonic movement, the Taurus Belt exhibits a very complicated stratigraphic sequence and lithological diversity.

The basement of the Ermenek Basin consists of Paleozoic and Mesozoic units, which are generally exposed at the southern part of the basin. The Paleozoic units are comprised of shale, limestone, dolomitic limestone and quartzite. While the Lower-Middle Triassic units contain limestone and shale, the Upper Triassic units consist of sandstone, conglomerate and limestone; the Jura-Cretaceous period is represented by dolomitic limestone (Gul and Eren, 2003). The Eocene and Paleocene sedimentary units contain fossiliferous limestone (Tepebasi Formation), which unconformably overlies the Cretaceous limestone and ophilotic mélange. Oligocene lacustrine deposits are represented by the Pamuklu Formation, including a coal layer of the Yenimahalle Formation, which unconformably overlies the Eocene-Oligocene units in the area. The Yenimahalle Formation has a great lateral extension in the Ermenek basin consisting of six main facies associations, which range from alluvial to offshore lacustrine deposits up to 300 meters thick. The Middle and Upper Miocene units that unconformably overlie the Lower Miocene unit in the basin are characterized by the Mut, Köselerli and Tekecati formations. The Koselerli Formation comprises claystone, limestone, clayey limestone and gravelly sandstone and marl deposits representing the center of the reef (reef core facies). The Mut Formation also consists of reef limestone deposits in a shallow marine environment, which includes clayey or fossiliferous limestone, and distinctive patch reefs are common in this formation (Gul and Eren, 2003). The last unit of the Miocene Age sequence in the basin is the Tekecati Formation, which consists of limestone, fossiliferous limestone, clayey limestone and mudstone as assessed typically shallow sea sediment belonging to a reefal environment (Yurtsever et al., 2005). These formations of the Middle and Upper Miocene also interfinger, and they have transitional contacts with one another (Figure 2).

A Digital Elevation Model (DEM) of the study area was constructed through the implementation of contour lines of 1/25000 scale topographic maps with an equidistance of 10 m. When considering DEM, the altitude values of the northern and southeastern parts of the study area vary from 1200 to 1860 m (Figure 3a), slope gradients exceed 90º from 0º (Figure. 3b), and the general physiographic trend of the study area was approximately S-SE (Figure. 3c).

FIELD INVESTIGATION AND ENGINEERING PROPERTIES OF STUDIED ROCKS

Rockfall events are observed in the very steep cliffs formed by jointed limestone; the cliffs increase abruptly from 1250 to 1850 m. The limestone of the Mut Formation does not consist of a single lithological property but also comprises a succession of different lithologies, Owing to its complex lithological structure, the field study was conducted in detail. A systematic sampling was conducted in order to determine the lithological and geomechanical properties of the Mut Formation with different facieses. Petrographic investigation of the limestone specimens from the systematic sampling along the X-X’ line (Figure. 4) of the formation consisted of routine observations under a polarized microscope. According to the results of the petrographic analysis, the specimens comprise four lithological units: fossiliferous limestone, claystone-marl, clayey limestone and limestone. On the other hand, based on petrographic analysis, weathering stage of each samples are determined. The results of the petrographic thin-section analysis are summarized in Table 1.

X-ray diffraction analysis (XRD) was also applied to the specimens in order to assess the relative quantity of minerals (see Table 1). The X-Ray diffraction and the thin-section analyses results show it is obvious that the Mut Formation comprises four different lithological units.

A series of systematic scan-line surveys was conducted during the field study in order to determine the orientation and spacing of discontinuities based on ISRM (1978) and ISRM (1981). According to the scan-line survey, five main discontinuity sets were determined via contour diagrams using a computer program called DIPS 5.1 (Rocscience Inc., 2002). The dip and dip direction of values of the major sets are 86/154, 85/210, 87/173, 84/077 and 55/155 (Figure 5). The discontinuities have high persistence (>20 m), very tight to very open aperture (from 0.1 mm to >10 cm) without infilling. The discontinuity surfaces are

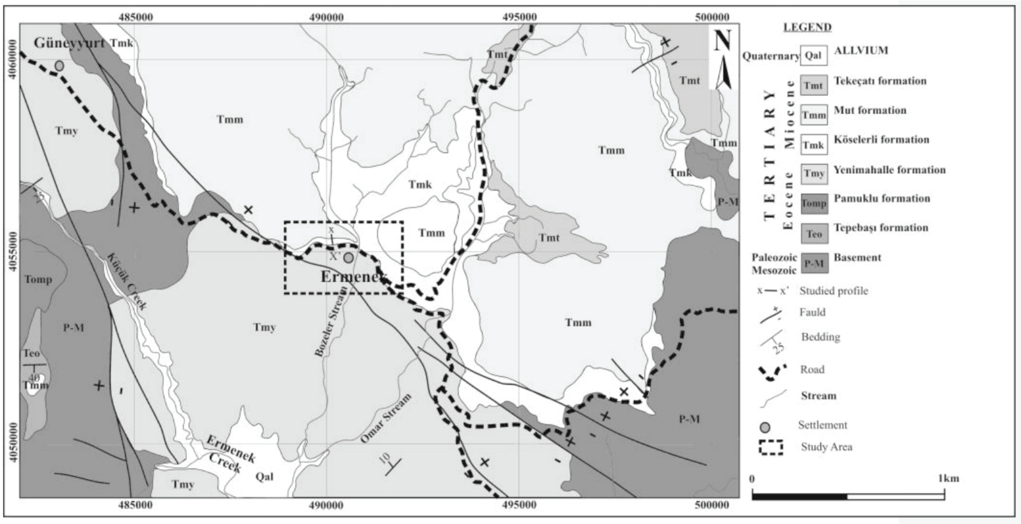


Figure 2. Geological map of Ermenek region.
Şekil 2. Ermenek bölgesinin jeoloji haritası.

rough, undulating and groundwater seepage does not exist through discontinuities surface. The average spacing value of the discontinuities was deemed to be 170 centimeters. The discontinuity spacing histogram is as shown in Figure 6.

Kinematic analysis of the discontinuities was conducted for the western, northern and eastern slopes of the study area. The analysis showed that two different failure types could be observed on the slopes. Although sliding is encountered as a main failure type on each slope, the toppling type of failure occurs only on the western and northern parts (Figure 7).

Fallen and hanging blocks in various dimensions were observed in the study area during the field work. For the purpose of identifying real approaches at rockfall modeling, the size, location and run-out distance of fallen blocks were determined (Figure 8). In addition to the various sizes of hanging blocks, different rockfall source areas were also observed during the field study (Figure 9). Moreover, block samples were taken in the field for laboratory testing. In addition to the block samples, systematic sampling was carried out from the bottoms to the tops of the slopes due to the different lithological and mineralogical features of the Mut Formation. The tests performed in the laboratory consisted of unit weight, apparent porosity, void ratio, water absorption by weight, water absorption by volume and uniaxial compression strength for each sampling zone. The procedures suggested by ISRM (1981) were considered in the application of tests. The average unit weight of the limestone samples (23.9 kN/m^3) was greater than the fossiliferous limestone (22.2 kN/m^3), claystone-marl (20.4 kN/m^3), and clayey limestone (21.5 kN/m^3) sample. The average uniaxial compressive strength values of limestone, fossiliferous limestone and clayey limestone were 55.3 MPa, 48.1 MPa and 36.1 MPa, respectively. The standard core sample cannot be extracted from highly weathered zones of claystone-marl for uniaxial compression tests. To cope with this difficulty, the Schmidt hammer index test was performed in the field. The average Schmidt hammer rebound number of the claystone-marl was obtained as 25, and the uniaxial compression strength value was found as 22.2 MPa indirectly. The results obtained from the tests are shown in Table 2.

ROCKFALL ANALYSIS

Various two- and three-dimensional software are available for the simulation of boulder fall and the computation of rockfall trajectories (Bassato et al., 1985; Falcetta, 1985; Bozzolo and Pamini, 1986; Hoek 1987; Pfeiffer and Bowen 1989; Azzoni and de Freitas 1995; Jones et al. 2000; Guzzetti et al. 2002). In this study, rockfall simulations of the Ermenek steep cliffs were conducted with Rockfall V.4 software (Rocscience Inc., 2002). Rockfall V.4 is a two-dimensional software program that performs the statistical analysis of rockfall, and its calculation engine behaves as if the mass of each rock is concentrated within an extremely small circle. In the simulation of

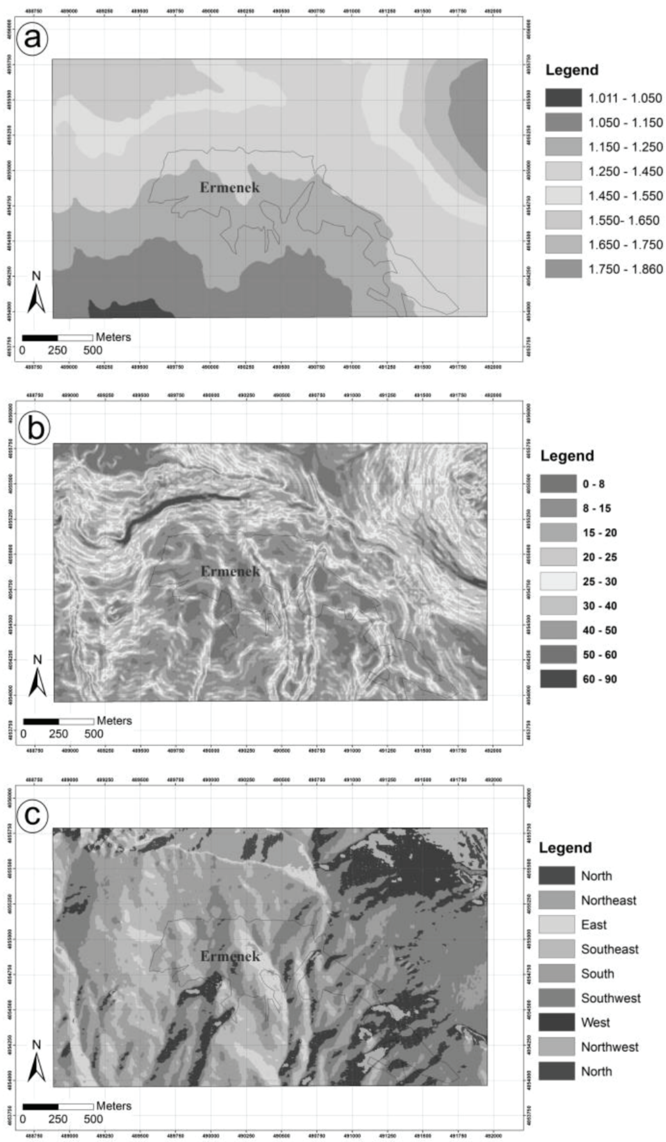


Figure 3. Reproduced maps of the study areas(a) altitude map, (b) slope gradient map, (c) slope aspect map.
Şekil 3. Çalışma alanine ait üretilmiş haritalar (a) yükseklik haritası (b) yamaç yönelimi haritası (c) yamaç eğimi haritası.

rockfall trajectories, any size or shape effects must be accounted for by an approximation of other properties (Rocscience Inc., 2002). Some crucial parameters are required in order to design block trajectories and rockfall analyses, including the coefficient of restitution (normal and tangential), slope geometry, roughness of slope and weight of hanging blocks. The slope geometry is obtained from 1/25.000 scale topographic map. When considering lithological features, distance from settlement district and location of rockfall source areas, ten slope profiles selected for rockfall simulation analysis (Figure 10). In the field study, hanging blocks are determined and weight of reachable block is calculated by using unit weight and volume of the rock (Figure 11). The hanging or detached blocks had various dimensions due to the discontinuity orientation, spacing and their mineralogical composition affected by weathering processes. The calculated hanging blocks weights vary between 75 kg and 9800 kg for different rockfall source areas (see Figure 9). For selected ten profiles, different rock masses (100 kg, 1.000 kg and 10.000 kg) were used in rockfall analyses considering block sizes which are ideally represented already falling

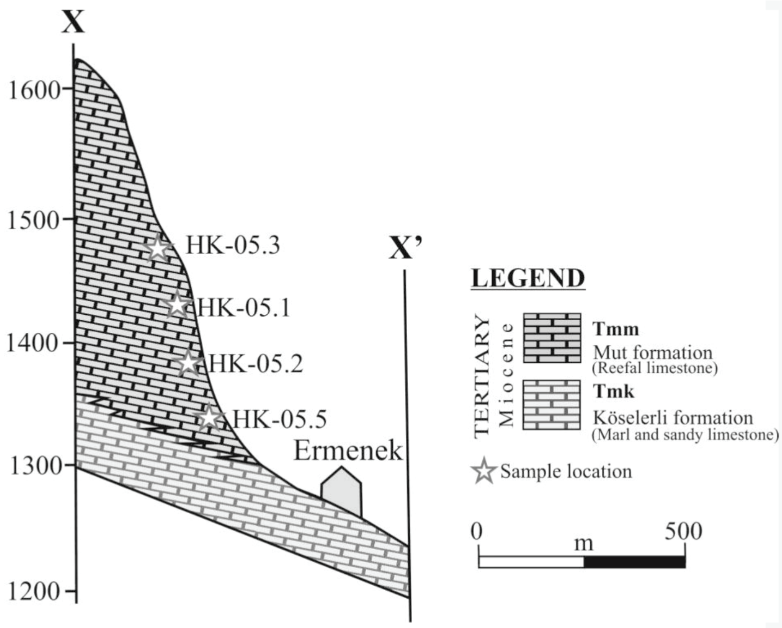
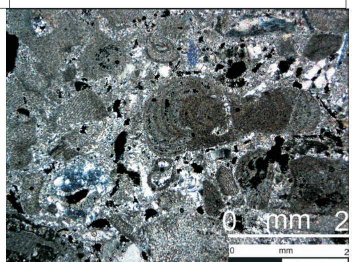
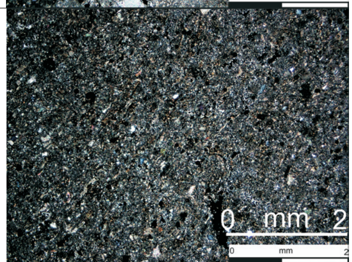
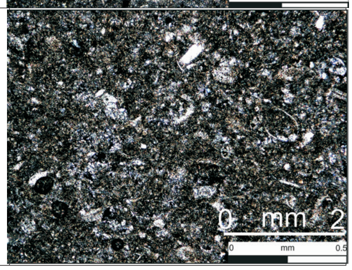


Figure 4. Systematic sampling locations along X-X' line.
Şekil 4. X-X' hattı boyunca sistematik örnekleme lokasyonları.

Table 1. Results of the thin-section petrographic and X-ray analyses
Çizelge 1. İnce kesit, petrografik tanımlama ve X-ışınları kırınım analiz sonuçları

Specimen No	Petrographic description	Mineral composition	Microscopic photograph
HK05-1	Slightly Weathered Limestone	Calcite, Quartz	
HK05-2	Weathered Clayey Limestone	Calcite, Qartz Chlorite, Dolomite	
HK05-3	Moderataly Weathered Claystone-Marl	Calcite, Dolomite, Smectite	

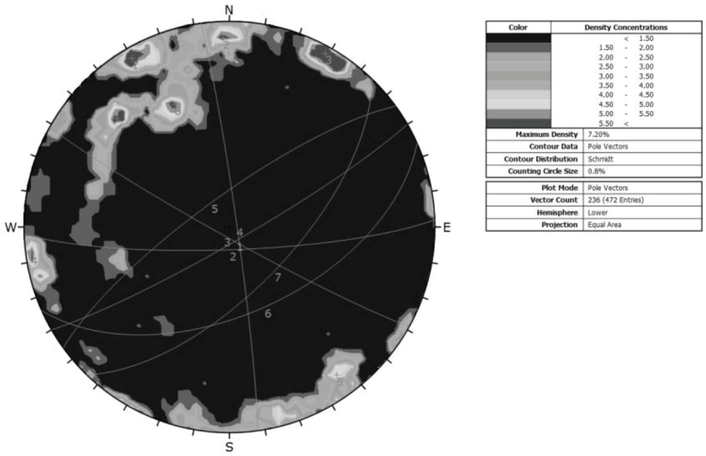


Figure 5. Contour diagram of major discontinuity sets.
Şekil 5. Hakim süreksizlik setlerinin kontur diyagramları.

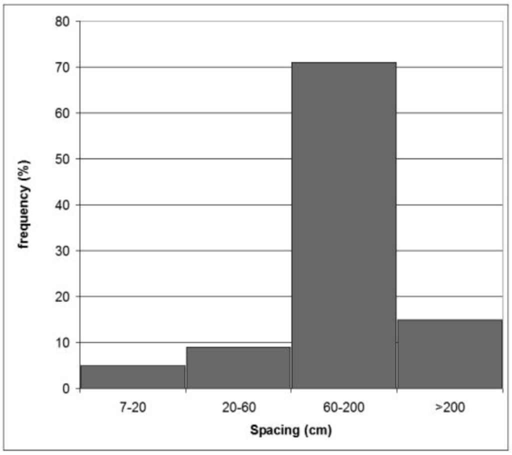


Figure 6. Discontinuity spacing histogram.
Şekil 6. Süreksizlik aralığı histogramı.

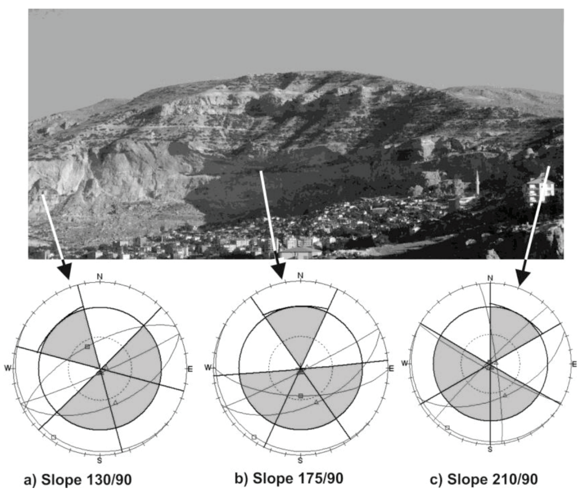


Figure 7. Kinematic analysis results of the slopes (grey areas represent main discontinuity sets obtained from Schmidt projection) .
Şekil 7. Şevlerin kinematic analiz sonuçları (gri alanlar Schmidt projeksiyonundan elde edilen ana sürekszilik setlerini temsil etmektedir).

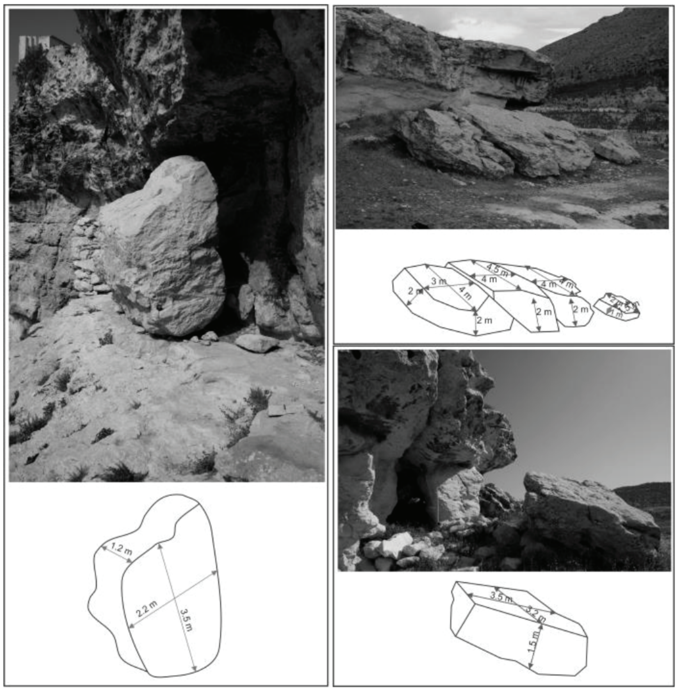


Figure 8. Dimensions of fallen blocks.
Şekil 8. Düşmüş bloklar ve boyutları Figure

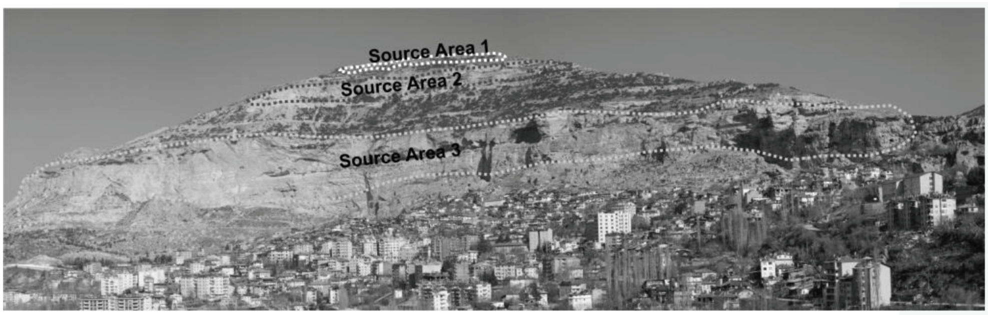


Figure 9. Rockfall source areas of Ermenek region.
Şekil 9. Ermenek bölgesindeki kaya düşmesi kaynak alanları.

blocks in the field. Initial velocity of blocks was preferred 0 m/s in the analyses considering the location of the each block.

The slope characteristics are very important factors for the rockfall event because of the fact that the behavior of the falling blocks control as the slope properties (Okura et al. 2000). The slope surfaces have played a considerable role in movement of falling or rolling blocks moving through the slopes. The slope faces are free from vegetation cover, they do not retard the movement of blocks. In this case, the blocks can be reached farther distance, on the contrary of the surface covered by vegetation or talus material. Because, the vegetation or talus material absorbs a high amount of the energy of the falling rock and will probably stop it (Hoek 2007). The retarding capacity of the slope surface material is expressed mathematically normal (R_n) and tangential (R_t) coefficient of restitution are affected by the composition of the material covering the surface and slope roughness. The coefficient of restitutions can be obtained from back analyses in the field or theoretical estimations (Pfeiffer and Bowen 1989; Evans and Hungr 1993; Robotham et al. 1995; Agliardi and Crosta 2003;

Table 2. Laboratory and field test results
Çizelge 2. Laboratuvar ve arazi deney sonuçları

	Limestone				**Clayey limestone**				**Claystone-Marl**				**Fossilliferous Limestone**			
	Max.	**Min.**	**Av.**	**St. Dev.**	**Max.**	**Min.**	**Av.**	**St. Dev.**	**Max.**	**Min.**	**Av.**	**St. Dev.**	**Max.**	**Min.**	**Av.**	**St.* Dev.**
Unit weight (kN/m^3)	24.35	23,25	23.95	0.31	22.04	21.24	21.57	0.22	20.75	20.24	20.44	0.19	23.63	20.50	22.28	0.99
Void ratio (%)	7.26	3.70	5.33	1.16	19.05	16.62	17.67	0.77	24.37	20.02	21.47	1.28	21.99	7.36	11.88	3.40
Porosity (%)	6.77	3.57	5.05	0.96	16.00	14.25	14.98	0.55	19.59	16.68	17.67	0.86	18.02	6.85	10.47	3.77
Water absorption by weight (%)	2.86	1.45	2.07	0.42	7.39	6.48	6,81	0.29	9.44	7.89	8.48	0.44	8.63	2.86	4.70	1.97
Water absorption by volume (%)	6.77	3.57	5.05	0.96	16.00	14.25	14.98	0.55	19.59	16.68	17.67	0.86	18.02	2.86	10.47	3.77
Uniaxial compressive strength (MPa)	73.40	46.29	55.35	10.58	39.88	32.45	36.12	2.57	27.46	18,17	22.20	3.90	59.69	29.47	48.11	12.08
**SHV	55				39				25				48			
Number of Samples	13				11				11				10			

*St. Dev: Standart Deviation
Av: Average
**SHV Schmidt hammer rebound number

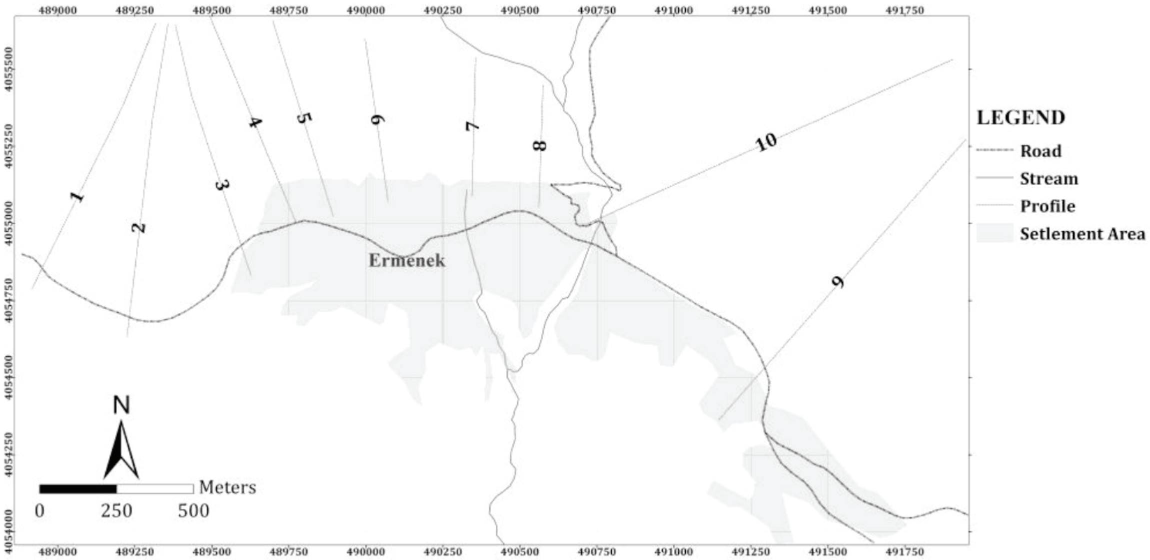


Figure 10. Rockfall profiles in the study area.
Şekil 10. Çalışma alanındaki kaya düşmesi profilleri.

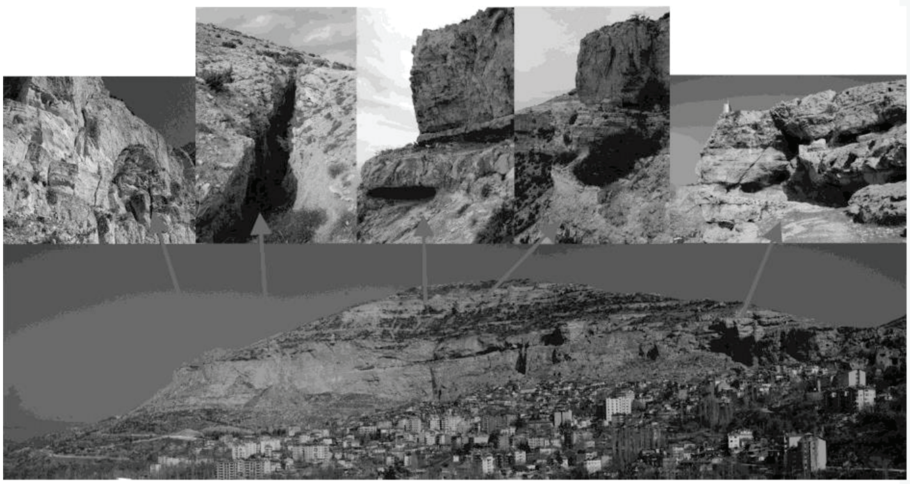


Figure 11. Photographs showing hanging blocks and their location in the study area (not to scaled).
Şekil 11. Çalışma alanındaki asılı bloklar ve yerlerini gösteren fotoğraflar (ölçeksiz)

Dorren et. al, 2004; Ulusay et al. 2006; Topal et al. 2007). Back analyses were performed to determine the coefficient of restitution with ten blocks in the field considering the size and the shape of the blocks and the slope characteristics (Figure 12). The results of the analyses, normal and tangential coefficients of restitution values belong the fallen rocks are determined as (0.33±0.04) and 0.63±0.19) respectively. In addition to coefficients of restitution, friction angle was determined by field back analyses as 32.5°. During the rockfall analyses 1000 rock blocks were thrown. The slope roughness which is another input parameter of rockfall simulation analyses was taken as 2° in based on the angle between rough surfaces. The input parameters used for rockfall analyses are given in Table 3.

The limestone and fossiliferous limestone units resisting against weathering, upper zones of weaker lithological unit claystone-marl accepted as rockfall source areas, based on field conditions (Figure 13). One of the typical examples of a rockfall trajectory

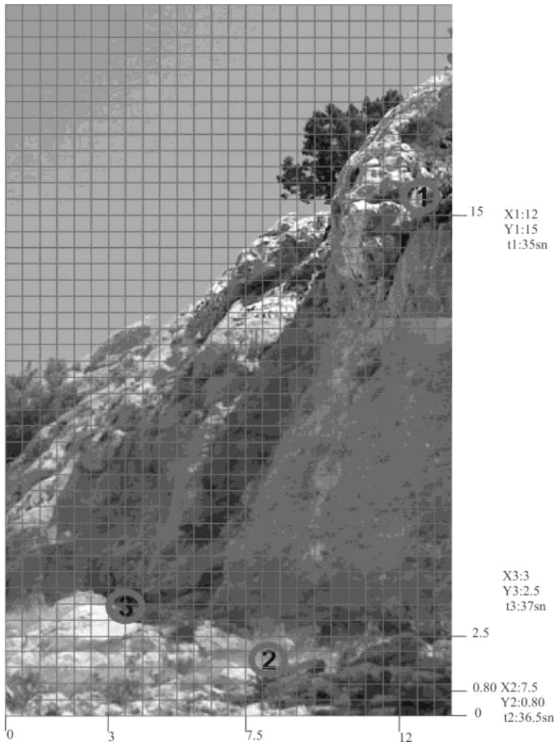


Figure 12. Back analyses in the field to determine the coefficient of restitutions.
Şekil 12. Arazide geri verme katsayılarını belirlemek amacayla yapılan geri analizler.

Table 3. Input parameters used in the rockfall analyses
Çizelge 3. Kaya düşmesi analizlerinde kullanılan girdi parametreleri

Parameter	**Value**
Number of rockfall	1000
Minimun velocity cut off (m/s)	0.1
Coefficient of normal restitution	0.33±0.04
Coefficient of tangential restitution	0.63±0.19
Friction angle(Φ)	32.5°
Slope roughness	2
Initial velocity (m/s)	0 ± 0.5

is given in Figure. 14 .The run-out distance, bounce height, kinetic energy and velocity of the blocks were predicted by rockfall analyses. According to the results of the analyses, maximum run-out distance reaches 660 m, kinetic energy 1750000 kJ, and velocity is 46.3 m/s for the free falling of the 1000 kg blocks. The results of analyses are summarized in Table 4. A rockfall danger-zone map was produced by using the results obtained from rockfall analysis, considering the maximum run-out distance of falling blocks Figure 15. According to the map, the areal extension of all blocks for each profile would be able to reach to the roads or settlement areas. It is apparent that the settlement area was located within the dan-

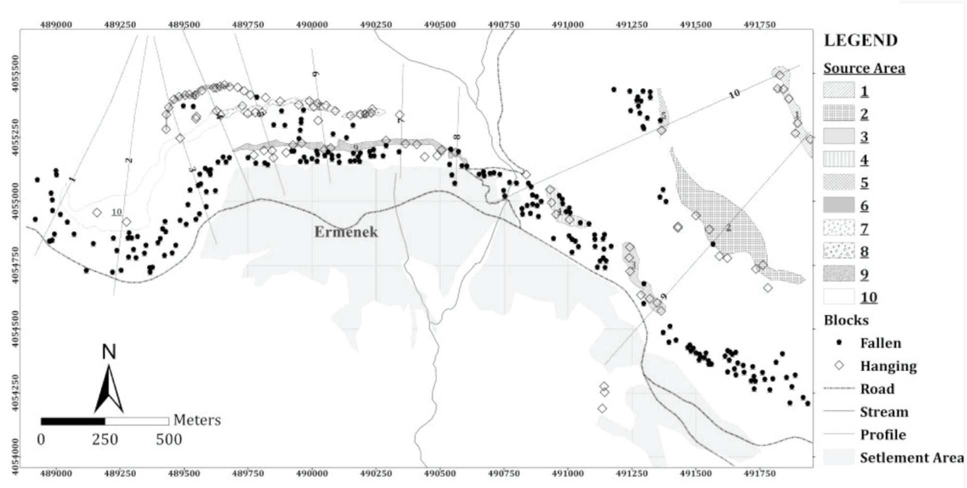


Figure 13. Distribution of fallen and hanging blocks of the rockfall source areas.
Şekil 13. Kaya düşmesi kaynak alanındaki düşmüş ve asılı blokların dağılımları.

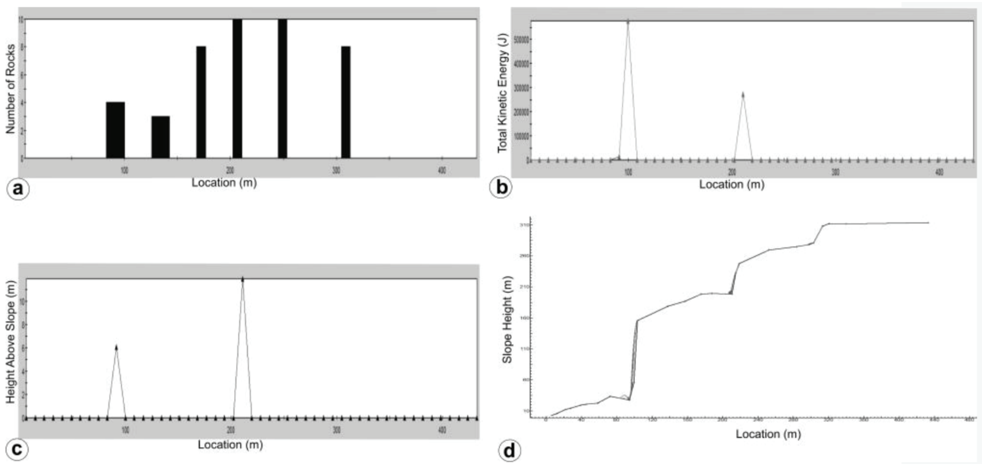


Figure 14. An example for the rockfall analyses results (profile 5) (a) runout distance (b) total kinetic energy (c) bounce height (d) the typical rockfall trajectory.
Şekil 14. Kaya düşmesi analizlerine bir örnek (profil 5) (a) kaçma mesafesi (b) toplam kinetic enerji (c) sıçrama yüksekliği (d) tipik bir kaya düşme analizi

ger zone. Although some preventive measures can be applied in order to reduce the rockfall hazard, it was directly dependent on the topographical and lithological factors of the potential rockfall source area. Moreover, the aesthetic and socio-economic conditions were limited to the existing preventive measurements. The construction of trenches, retaining walls (barriers), wire meshes, cable/stretching nets, rock bolting and evacuation of the danger zone can be used as preventive measures in the rockfall areas. However, the most widely known remedial measures in literature are not proper in the study area, given its topographical and lithological features. Thus, to apply trenching and fencing is not possible because the large hanging blocks have relatively high kinetic energy and bounce height. Rock bolting cannot be applied at higher elevations because the slopes have considerably steep cliffs and large block sizes. Therefore, it is recommended that the hanging blocks in the reachable locations should removed while taking safety measures. Although the total evacuation of the danger zone is not preferred by the residents, it is, in the opinion of the authors of this study, indispensible in the study area.

Table 4. Results of the rockfall analyses
Çizelge 4 .Kaya düşmesi analiz sonuçları

Profile Number	Maximum Slope Height (m)	Weight of block (kg)	Runout distance (m)		Bounce height (m)		Kinetic energy(kJ)		Velocity (m/s)	
			Max	Min	Max	Min	Max	Min	Max	Min
		100	683	170	7	0.5	14000	1000	16	1
1	88	1000	585	195	3	0.5	120000	5000	14	2
		10000	480	160	7.25	0.5	1400000	10000	16	2
		100	535	233	2.8	0.5	2200	1025	6.3	2
2	33	1000	280	233	3	0.5	18200	1247	7.21	1.02
		10000	277	222	3.2	0.45	62033	6300	3.27	1.03
		100	272	115	13.25	1.23	14027	60150	16.29	8.23
3	334	1000	275	48	19	2	1750000	7350	46.3	8.23
		10000	263	72	108.5	13.5	11200000	860000	63.5	9.87
		100	323	75	68.3	4.3	34500	6350	28.43	3.45
4	145	1000	312	80	11.8	3.05	583400	54000	34.42	3.02
		10000	325	82	13.8	6.32	6973000	425000	33.25	2.1
		100	273	32	57.32	11.3	64300	8920	36.32	12.32
5	123	1000	281	40	68.32	4.06	670000	33000	33.24	4.2
		10000	283	45	68.3	4.23	6270000	4350000	33.5	6.7
		100	235	12	8	2	102500	5000	46	3.8
6	103	1000	232	11	6.4	1.8	958000	5800	45	4.2
		10000	88	43	18	3.2	10500000	560000	43.5	3.8
		100	7.8	2.8	1.2	0.2	8320	1823	12	5
7	336	1000	7.5	1	1.1	0.18	83000	31000	11.5	7
		10000	7.6	1.2	0.8	0.2	7000000	480000	11.5	3
		100	77	23	15	3.8	14300	3200	16.7	2.9
8	104	1000	76	24	55	12	870000	38000	45	5
		10000	34	27	57	8	8650000	43000	42	7
		100	249	215	18	3	72000	11000	38	11.5
9	95	1000	248	235	21	3.2	630000	42000	36	8
		10000	248	234	24.5	0.5	7120000	1050000	37	12
		100	670	480	1.9	0.5	24500	1800		
10	68	1000	660	510	2.4	0.5	653000	43500	34.5	5.2
		10000	660	512	3	0.25	6250000	254000	34	4.3

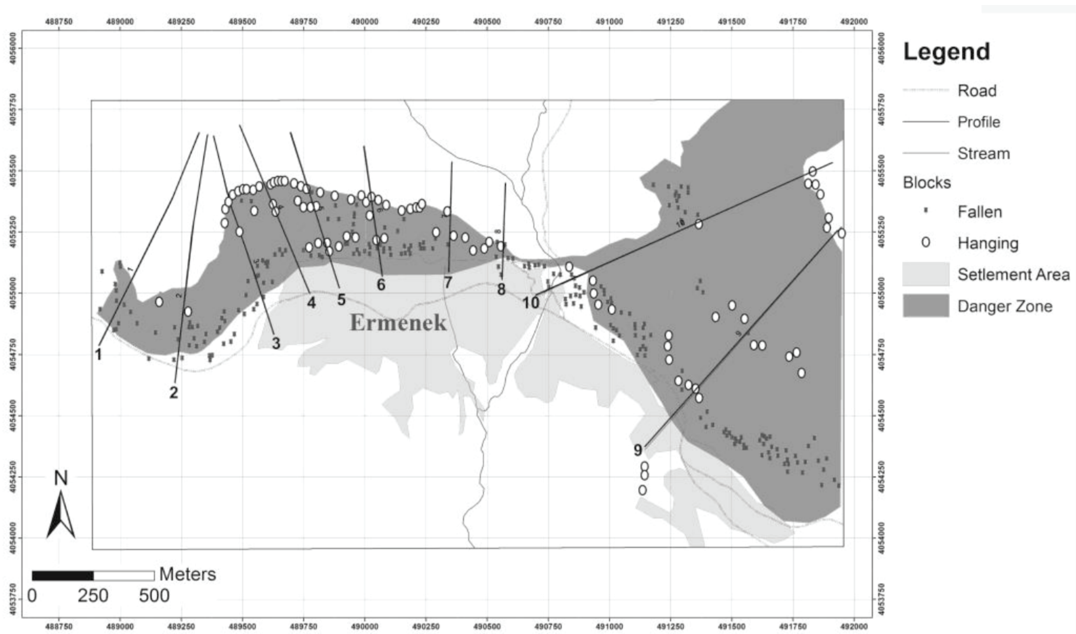


Figure 15. The map showing the rockfall danger zone of study area
Şekil 15. Çalışma alanındaki kaya düşme tehlikesi zon haritası

RESULTS AND CONCLUSIONS

Ermenek is a spectacular settlement area located in between very steep cliffs an average elevation of 1850 m. The settlement has been subjected to rockfall events several times, and such events have resulted in losses of life and property. During the fieldwork, and depending on laboratory test results, the rockfalls were initiated by discontinuities, weathering processes and the characteristics of limestone having different lithological facieses. Considering the scan-line survey, five main discontinuity sets were determined. The findings revealed that the limestone formations comprise four lithological units: fossiliferous limestone, claystone-marl, clayey limestone and limestone. Thus rockfall occurs at the uppermost level of limestone and fossiliferous limestone due to the existence of weaker claystone-marl at the lower levels of the facies.

Two-dimensional rockfall analyses were performed using the data collected from field study and laboratory test results along ten profiles. Rockfall analyses indicated that the roads and the settlement area were remaining in the rockfall danger zone. Considering the topographical and lithological limitations, commonly used remedial measures are not preferred in the present study. It is recommended that total evacuation and the clearing of loose blocks in accessible locations be performed.

ACKNOWLEDGEMENT

The authors would like to thank reviewers for their valuable comments on the manuscript. This research is supported by The Scientific and Technological Research of Turkey, TUBITAK (Project No:107Y071).

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