



Rockfall analysis and risk assessment on steep slopes of the roadway (Zonguldak, Turkey)

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Abstract

Zonguldak city is a mountainous area in Turkey's Western Black Sea. In such mountainous areas, it is highly recommended to undertake precautions measures due to sudden and uncertain risk arising from rockfall events causing significant damage to infrastructures and structures. Therefore, this phenomenon is investigated as an important and special issue in civil and mining engineering. The main objective of this study is to investigate the possible rockfall events and risk assessment of the potential rockfall that may occur near the Zonguldak-Istanbul roadway slopes. In Zonguldak mountainous area, the rockfall event occurred due to presence of the discontinuities in the rock, tectonism of the rock units and rainfall factors, and a combination of these factors. For this purpose, a detailed field observation on slope and rock characteristics has been carried out. In this present study, rockfall analysis has been performed out on two selected slope profiles taken in one location by using of the Rocfall numerical analysis program based on the lumped mass method. Thus, bounce height, fall-out distance, velocity, and kinetic energy of the blocks along each survey has been analysed. Therewithal, the assessment of rockfall potential hazard has been carried out by applying of the Evolving Rockfall Hazard Assessment (ERHA) method. As a result, the investigated area is defined as a moderate to high risk category and necessary protective measures are recommended.

Keywords Rockfall analysis · Risk assessment · Steep slope · Limestone

Introduction

Instabilities in rock masses bring along significant geological hazards (Ulamış and Kılıç 2020). Especially, rockfall phenomenon which is defined as a widespread geological disaster that occurs mostly in mountainous regions, due to the frequency and density of occurrence (Ulamış and Kılıç 2020; Liao et al. 2020). Rockfall occurs in the form of toppling, bouncing, rolling, and sliding of a single rock or small group rocks which independently moving from an inclined or steep slope surface. Rockfalls are an extremely rapid evolving events and, falling rock blocks may be reached far points (Ferrari et al. 2016).

Therefore, rockfalls can cause serious damage to urban areas, engineering structures and lives (Chau et al. 2003; Ferrari et al. 2016; San et al. 2020).

Rockfalls have a lower level of economic risk than would be caused by large scale landslides. However, rapid movements of falling rock blocks can cause numbers of fatalities to the compared the other landslide types (Hoek 2007). The discontinuities, force of gravity, mechanical weathering, the presence of water, etc. are acting an important role in the detachment of rock blocks from the slope surface. Factors affecting rockfall are shown in detail in Fig. 1. From Fig. 1, the factors that cause and affect rock fall are evaluated in three main groups as structural, environmental, and manmade factors. Therewithal, rockfall phenomenon may occur depending on the presence of one or more of these factors.

The movement of each rock block that falling from the certain slope surface, analysed in terms of velocity, bounce height, and run out (Nagendran and Ismail 2019). Generally, rockfalls are difficult to predict due to the uncertain, sudden, and dangerous landslide movement (Mineo et al. 2018; Nagendran and Ismail 2019). For this reason, potential areas of rockfall hazard should be studied by using different

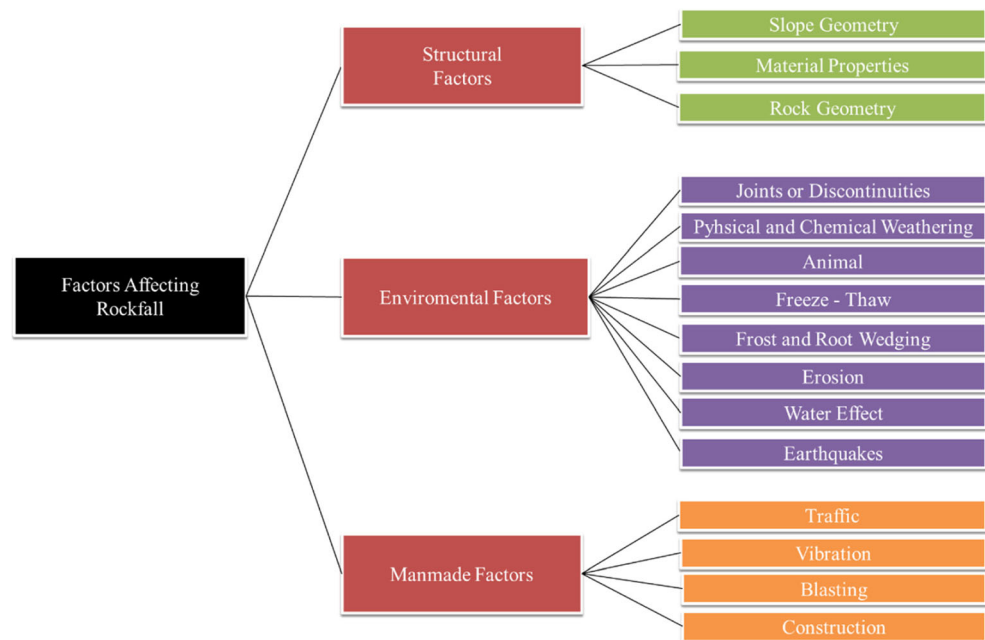
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Fig. 1 Factors affecting rockfall (modified from Ashfield 2001; Geniş et al. 2017)



investigation methods. Within the scope of rockfall potential assessments, different analysis techniques have been used including experimental studies, numerical models, geographic information system-based evaluations, and two or three dimensional approaches (Binal and Ercanoğlu 2010; San et al. 2020). In this context, many studies have been carried out by numerous researchers on the problem of rockfall (Ritchie 1963; Raetzo et al. 2002; Crosta and Agliardi 2003; Corominas et al. 2005; Ulusay et al. 2006; Charalambous and Sakellariou 2007; Topal et al. 2007, 2012; Saroglou et al. 2012; Akin et al. 2014; Antoniou 2013; Kaya and Topal 2015; Geniş et al. 2017; Mineo et al. 2018; Zhu et al. 2018; Ansari et al. 2018; Kayabaşı 2018; Zhu et al. 2018; Korkanç et al. 2018; Saroglou 2019; Hepdeniz 2019; Sazid 2019; Ulamış and Kılıç 2020; Liao et al. 2020; San et al. 2020; Liu et al. 2020; Depountis et al. 2020). Besides, for the estimation of rockfall, rockfall hazard assessment systems are also widely used (Youssef et al. 2003; San et al. 2020).

Some of qualitative methods, that are Rockfall Hazard Rating System (RHRS) (Pierson (Pierson and Van Vickle 1993), Swiss code (Lateltin et al. 2005), UDOT Rockfall Hazard Rating System (Pack et al. 2006), Colorado Rockfall Hazard Rating System (Russell et al. 2008), and Evolving Rockfall Hazard Assessment (ERHA) (Ferrari et al. 2017), are used in the literature (Ulamış and Kılıç 2020).

The period from 1950 to 2008 in Turkey, the total number of rockfall events in 79 provinces and 1703 settlements is 2956, and the number of affected disaster victims is 22,157 (Gökçe et al. 2008). Hazard potential due to rockfall is particularly concentrated in the Black Sea and Eastern Anatolia regions (Gökçe et al. 2008; AFAD 2020). Environmental features such as increasing

rainfall and temperature differences between day and night play an important role on the rockfall potential in these regions. Environmental features such as increasing rainfall and temperature differences between day and night play an important role on the rockfall potential in these regions. In addition, the Black Sea and Eastern Anatolia regions consist of high mountains due to their geographical structure (Gökçe et al. 2008; Ercanoglu and Gokceoglu 2002; Yilmaz et al. 2012).

In the last decade, many rock falls have occurred in the rocks dominated by limestone in the Zonguldak region (Fig. 2), and this situation has seriously affected the highways and railway lines. Major rockfall events in Zonguldak for last decade are given in Table 1. When Table 1 is examined, rockfall events mostly occurred between September and March when heavy rainfall occurs. The average amount of precipitation between these months is 124.7 mm (MGM 2021). Especially due to the heavy rainfall in the region, limestone rocks may dissolve. This situation causes the blocks on the slope surface to separate from the bedrock and move independently. Besides, the presence of discontinuities and their relative positions increase the rock fall potential significantly. Therefore, it is a necessity to assess rockfall potential and make necessary improvements.

In this study, it is aimed to investigate the potential of rockfall on the slopes in Polisevi region located on the Zonguldak-Kozlu roadway and to determine the appropriate remedial suggestions. In this context, firstly, the geological characteristics of the study area were defined by field studies. Thereafter, laboratory studies were carried out on limestone samples taken from

Table 1 Major rockfall events (2010–2021) near Zonguldak Province

Date	Location	Average maximum fallen block size (m)	Events
5 September 2010	Zonguldak-Kozlu Roadway (oil station)	0.5 × 0.3 × 0.4	N/A
25 March 2011	Zonguldak-İstanbul Roadway	2.5 × 1.6 × 1.5	One lane road closed
6 January 2013	Zonguldak-Ereğli Roadway	0.8 × 0.3 × 0.5	N/A
26 February 2014	Zonguldak-Kozlu Roadway (Oil Station)	1.2 × 0.9 × 0.8	Car damaged
30 December 2014	Zonguldak-Ereğli Roadway	0.7 × 0.5 × 0.5	Car damaged
7 February 2015	Zonguldak-Ankara Roadway (Gökgöl Cave)	0.4 × 0.4 × 0.2.	N/A
1 January 2016	Zonguldak-Ankara Roadway (Gökgöl Cave)	2.5 × 1.5 × 1.0	Road closed
31 January 2016	Zonguldak-Ankara Roadway	0.9 × 0.9 × 0.7	N/A
28 October 2016	Zonguldak-Ereğli Roadway	0.3 × 0.2 × 0.15	Car damaged
19 June 2017	Zonguldak-Kozlu Roadway	1.2 × 0.4 × 0.4	N/A
20 September 2017	Zonguldak-Kilimli Roadway	0.4 × 0.2 × 0.1	N/A
25 February 2018	Zonguldak-Ereğli Roadway	1.3 × 1.2 × 0.9	One lane road closed
15 September 2018	Zonguldak-Ereğli Roadway	0.5 × 0.2 × 0.2	Car damaged
10 December 2018	Zonguldak-Kozlu Roadway (study area)	0.4 × 0.3 × 0.2	N/A
08 October 2019	Zonguldak-Ereğli Roadway	4.0 × 2.0 × 1.5	Road closed
13 January 2021	Zonguldak-Ereğli Roadway	0.3 × 0.3 × 0.2	Car damaged
24 March 2021	Zonguldak Bus Station	0.7 × 0.5 × 0.4	Building damaged
26 March 2021	Zonguldak Bus Station	1.5 × 0.8 × 0.5	Building damaged
26 March 2021	Zonguldak-Kozlu Roadway (study area)	1.0 × 0.8 × 0.8	One lane road closed

Note: The whole rockfall event occurred within the limestone unit

different points in the field and the physical and mechanical properties of the rock were obtained. Finally, on the rockfall potential areas identified in the study area, two-dimensional rock fall analyses were performed

using computer software Rocfall (v.4.0) (Rocscience 2012) and the results were discussed. In addition, the assessment of rockfall potential hazard has been evaluated by using the Evolving Rockfall Hazard Assessment

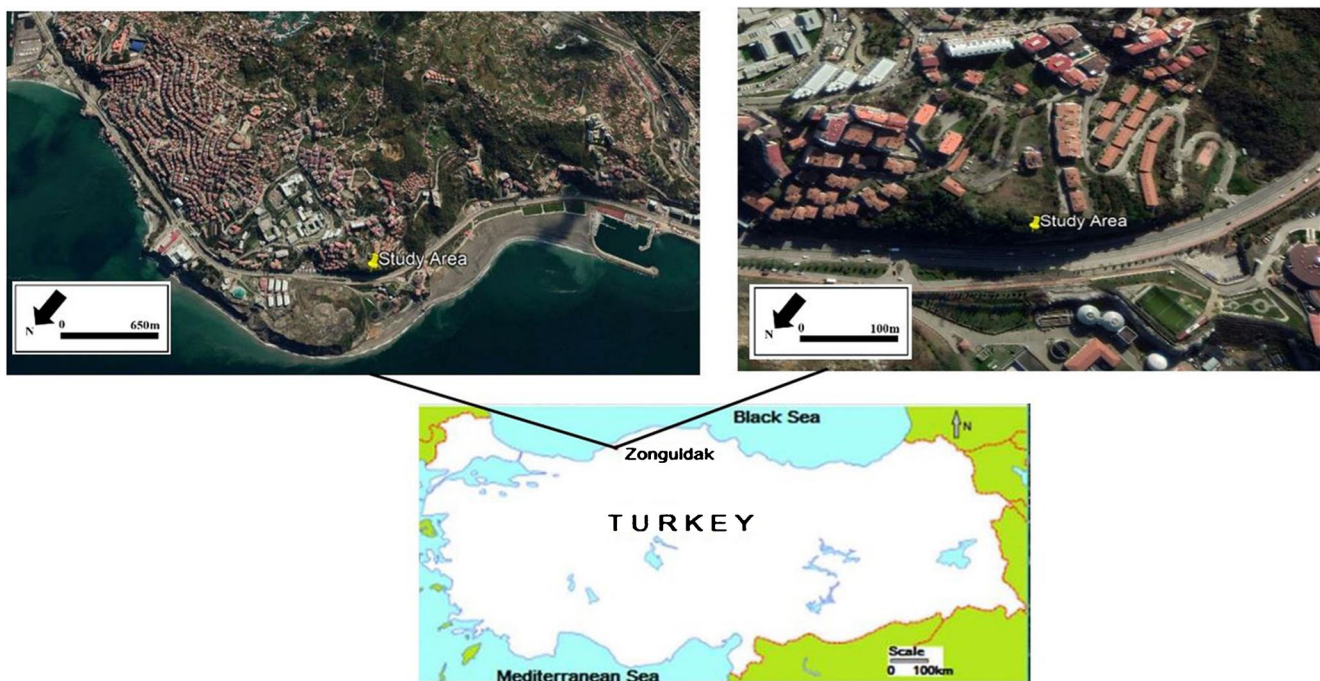


Fig. 2 Location map of the study area

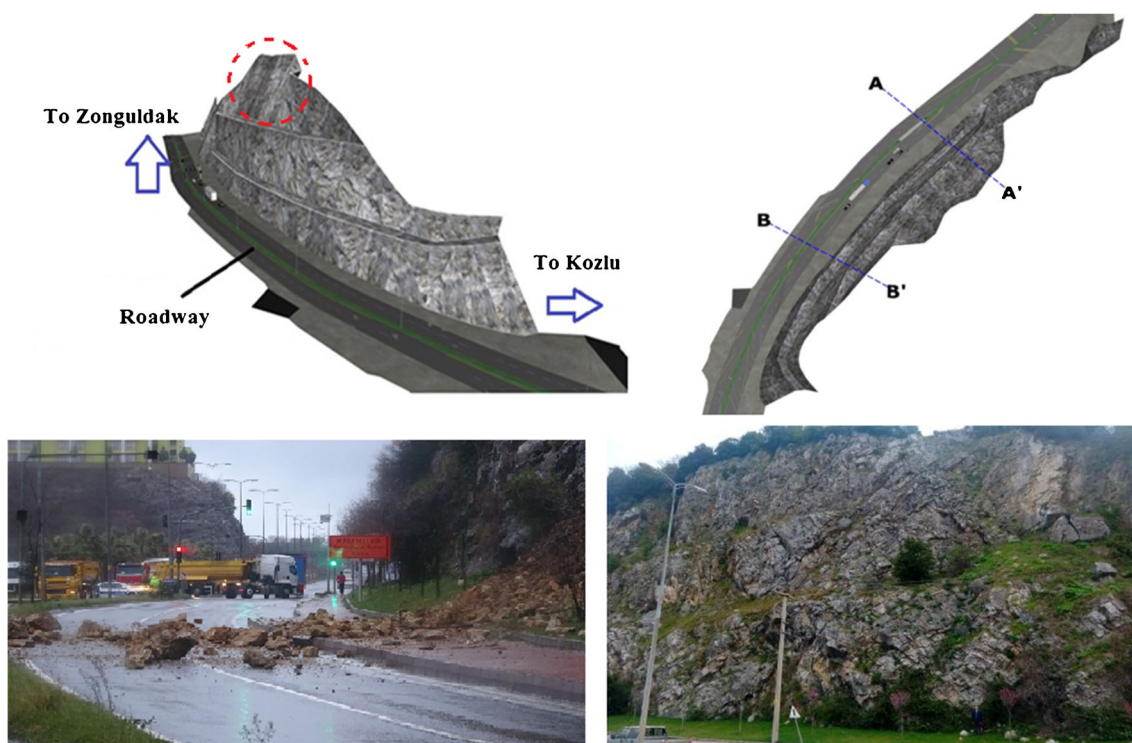


Fig. 3 Views of the slope sections and the last rockfall incident (URL-1 2021)

(ERHA). As a result of this study, remedial measures are proposed against rockfall in the study area.

Methods

Geology of study area

Zonguldak province is the largest area in Turkey where the Carboniferous Northwest Anatolian Hardcoal basin is exposed. The Cretaceous units overlying the Carboniferous units are located on the Zonguldak Kozlu roadway in the city of Zonguldak. The study area is an approximately 250-m region at the Polisevi location on the Zonguldak-Kozlu roadway (Fig. 2). Stratified sedimentary units spreading on the slopes of the study area are composed of sedimentary rocks known as carbonated İnalı Formation. The unit is generally composed of platform-type carbonated micritic limestones, beige-greyish white, light grey in colour, medium and thick bedded, locally massive, micritic character, mostly hard-rugged, durable, abundant cracked, and local faulty appearance. Calcite-dolomite and yellow-brown coloured clayey mylonitic fillings, which provide secondary development in the joint set and faults, are observed (Keskin 2019). The average thickness of the limestones varies between 10 and 50 cm. Discontinuities and weathering caused by orogenic movements developed during and after the deposition processes

of the units created areas suitable for mass movements such as sliding and rockfall.

Field and laboratory studies

Within the scope of the field study, the study area was examined in detail and rockfall potential areas were determined. The last rockfall incident in the study area occurred on March 26, 2021, after heavy rainfall. Fortunately, there was no loss of life in this rock fall incident, but the roadway was temporarily closed to traffic (Fig. 3). Fallen rock blocks in various dimensions have observed in the research area before. As a result of rockfall event, a large number of rock blocks (total of 68) has fallen along the main transportation road. The largest fallen block (has a dimension $1.0 \times 0.8 \times 0.8$ m

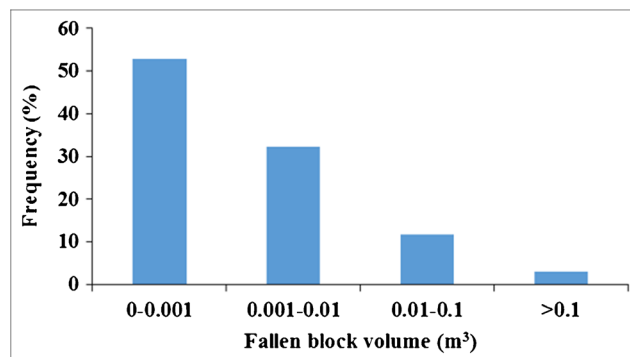


Fig. 4 Frequency of the fallen rock block volume

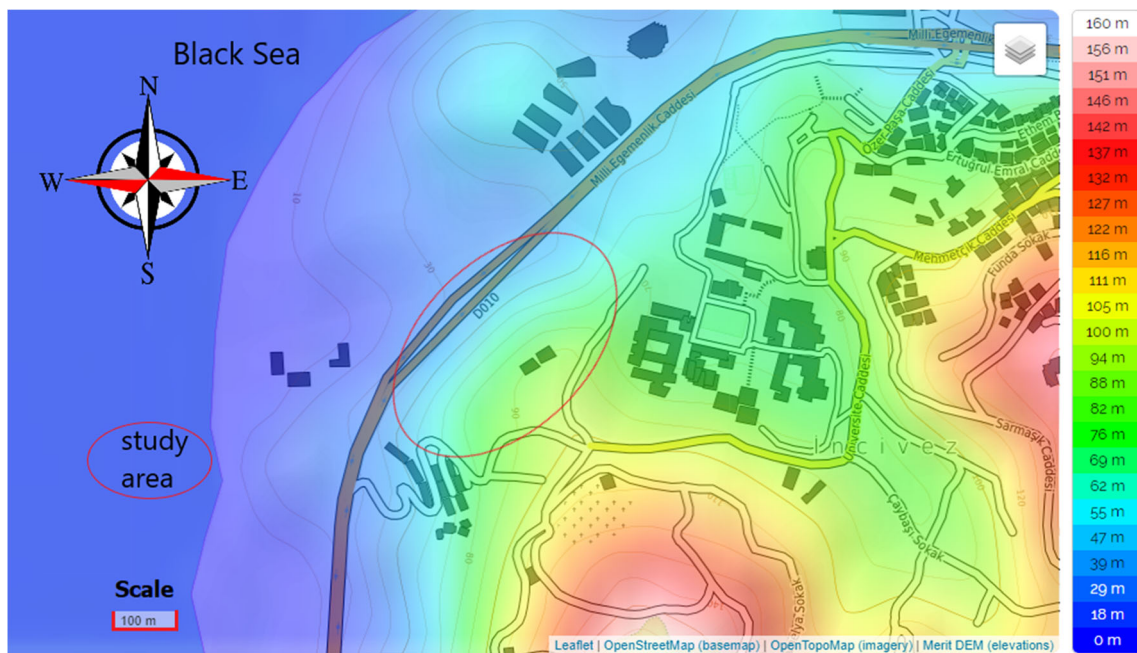


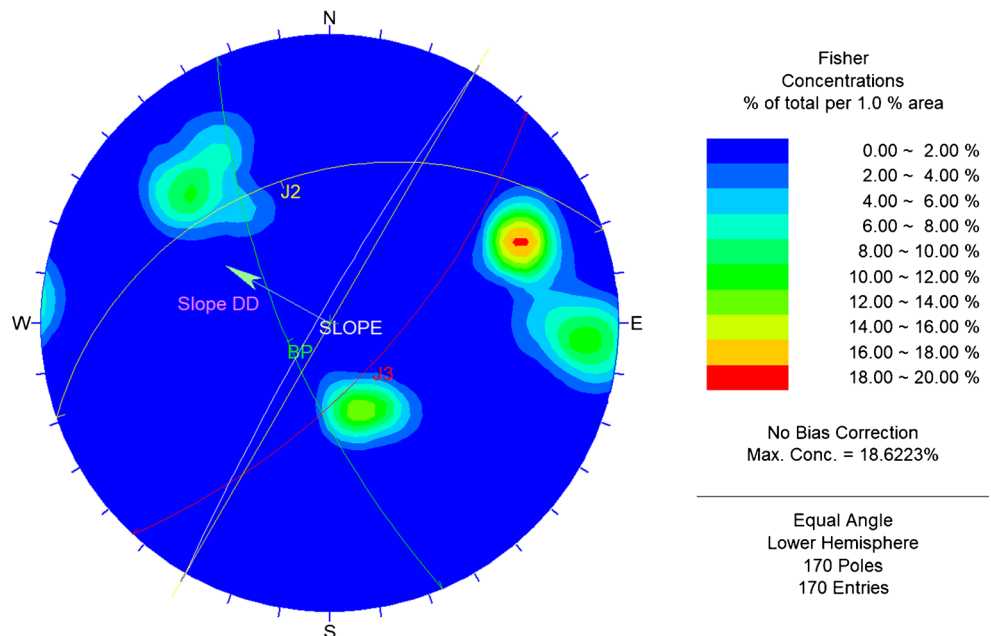
Fig. 5 Altitude map of the study area (URL-2 2021)

corresponding to approximately 1600 kg) has observed in the field area during last event. Rock blocks are less than 0.001 m³ which is 53% of total fallen blocks. On the other hand, some blocks up to 0.1 m³ (Fig. 4). The roadway slope is of high slope angle, and most of the falling blocks have reached the roadway (Fig. 5).

In addition, discontinuities data (bedding plane, joints, dip and dip direction, etc.) from slope surface were collected on the limestone units. Besides, block samples were taken from the field in order to determine the physical and mechanical properties of limestone.

The dip and dip direction measurements of 170 discontinuities were taken in the study area. The rock mass contains a bedding plane and two sets of discontinuities. A contour diagram for the distribution of discontinuity orientations was drawn using the Dips (v.5.1) (Rocscience 2015) program (Fig. 6). The bedding plane has a dip direction of 247° and a dip of 72°. The dip direction and dip angle of the second and third joint sets that dominate the terrain, are 341°/35° and 133°/67°, respectively. Considering the positions of the discontinuities with each other, rock blocks have formed a fall potential on the slope surface. According to the kinematic

Fig. 6 Contour diagrams of discontinuity orientations



analyses results, there are no potential for slide, wedge, and toppling failure types depending on discontinuity and slope orientations ($300^\circ/85^\circ$). Details of the kinematic analysis are not provided in this study.

Discontinuity measurements were carried out according to ISRM (2007). In this context, the orientation, spacing, aperture, persistence, filling, roughness, and presence of ground-water were examined separately. The average discontinuity spacing is 130 mm and “close spacing” class. The persistence of discontinuity is < 1 m, and it is determined to be in the “very low persistence” class. The average aperture of the discontinuities varies between 1 and 5 mm, and the “open/moderately wide” class (ISRM 2007). There was determined that 1–5 cm calcite fillings among the discontinuities. According to field observations, there had been no ground water income seen. However, considering that Zonguldak region is a region with heavy rainfall, “wet surface conditions” can be considered for the worst conditions. The volumetric joint count was determined as 9.5 joints/m³ and therefore it was defined in the “medium sized blocks” class. Depending on the volumetric joint count, the rock quality designation (RQD) value was determined to be 83% on average (ISRM 2007). RQD value is defined as “good quality rock” according to Deere and Deere (1988) (Ulusay 2010). Roughness of the discontinuity surfaces varies between “ondulating-slickensided / planar-rough”. The roughness coefficient of the discontinuities is easily determined using a profilometer in the field. According to ISRM (2007), the roughness coefficient was taken as 4.

Physical and mechanical properties of limestone are determined according to ISRM (2007). For this purpose, NX type core samples were taken from the blocks and the samples were sized according to the test method. In this context, uniaxial compressive strength (UCS), Brazilian tensile strength (BTS), and triaxial compressive strength tests were carried out. In addition, the physical properties (unit volume weight, water content, porosity, and void ratio) of the rock were determined by Özcan and Aslan (2016). The results are presented in Table 2.

According to the laboratory results given in Table 2, the average UCS values of limestone was determined as 105 ± 21.5 MPa and it was defined in the “very high” class (ISRM 2007). The Brazilian tensile strength value was obtained as 12.6 ± 2.85 MPa and is in the “very high” strength class according to the classification proposed by Backstrom et al. (2009). The cohesion and internal friction values were obtained from the triaxial compressive strength tests were determined as 22.8 MPa and 45.3° , respectively. In addition, the physical properties of the rock have been determined. Dry and saturated unit weight values were determined as 26.3 and 26.8 kN/m³, respectively. The porosity percentage of the rock was determined as 4.3. The void ratio was almost non-existent and

Table 2 Physico-mechanical properties of limestone

Parameters	Average
Dry unit weight (kN/m ³)	26.3 ± 0.5
Saturated unit weight (kN/m ³)	26.8 ± 0.4
Water content (%)	1.61 ± 1.11
Uniaxial compressive strength (MPa)	105 ± 21.5
Brazilian tensile strength (MPa)	12.6 ± 2.85
Cohesion (MPa)	22.8
Internal friction angle ($^\circ$)	45.3

was achieved as 0.05 and the water content was found to be 1.61%. The degree of saturation was determined as 100%.

Recent years, the accepted rock mass classification systems are widely used in order to define the rock mass quality. In this study, rock mass rating classification (RMR) proposed by Bieniawski (1989) was used to determine the rock mass. Considering the discontinuity and strength properties of the rock, the basic RMR was calculated as 78. According to Bieniawski (1989), the basic RMR value is in the good rock class. In addition, the corrected RMR value was calculated as 69 by adding the effect of discontinuity and other correction factors to the basic RMR score.

Results

Rockfall analysis

The rockfall event may vary depending on the geometric and mechanical properties (friction, roughness, rolling resistance, restitution coefficient, etc.) of the slope and rock blocks (Ritchie 1963; Ansari et al. 2014; Kaya and Topal 2015).

Rock blocks falling from a steep surface indicate to movement behaviour as free fall, bouncing, rolling, or sliding. However, in some cases, rockfall events can be observed as a combination of these movements.

Table 3 Input parameters used in rockfall analyses

Parameter	Value
Number of block throws	1000
Initial velocity (m/s)	0.0
Throw type	Random
Friction angle	$38\text{--}50^\circ$ (mean 44°)
Slope surface roughness (JRC)	(2–5) (mean 4) (ISRM 2007)
Tangential restitution coefficient (Rt)	0.255 ± 0.45
Normal restitution coefficient (Rn)	0.65 ± 0.10

Table 4 Summary of the rockfall analyses results for the profile

	Mass of the falling block (kg)	Maximum bounce height (m)	Maximum total kinetic energy (kJ)	Maximum velocity (m/s)
A-A'	10	10	1.8	18.7
	100	9.7	18.4	19
	500	10.1	93.9	19.1
B-B'	10	9.5	1.0	14.2
	100	9.4	10.0	14.0
	500	9.5	50.7	14.1

In this study, Rocfall (v.4.0) (Rocscience 2012) computer program was used to evaluate the rockfall potential and 2D rockfall analyses were performed. The Rocfall (v.4.0) program is highly effective and easy-to-use software for rockfall analysis. Therefore, in rock fall analyses (Binal and Ercanoğlu 2010; Ansari et al. 2014; Kaya and Topal 2015; Taga and Zorlu 2017; Ansari et al. 2018; Kayabaşı 2018; Nagendran and Ismail 2019; Sazid 2019; San et al. 2020) is widely used. The Rocfall (v.4.0) program uses particle analysis to simulate the motion of the rock block (San et al. 2020). Thus, the bounce height, kinetic energy (intensity), and run out distance of the rock blocks falling from the slope surface can be determined. Rocfall (v.4.0) uses “Lumped Mass” approach for simulation of fall and the computation of rockfall trajectories. In this approach, the block is treated as a lumped mass which neglects the three-dimensional aspects of the block such as shape and dimension (Rocscience 2002; Ku 2013; Akın et al. 2014; Taga and Zorlu 2017; Geniş et al. 2017). Also, the latest version of Rocfall (v.8.0) uses the “Rigid Body Mechanics” option that allows multiple rock shapes such as sphere, cube, or block. The lumped mass and rigid body analysis options use completely separate analysis engines within RocFall (v.8.0). Two methods can give equivalent results if the rock shape is modelled as a very small sphere (Rocscience

2021). Otherwise, the use of rigid body analysis can increase the reliability of predicting rockfall trajectories.

Rockfall analyses were carried out in two possible problematic section profiles observed in the study area. Input parameters used in the analysis are given in Table 3. In the analyses, number of block throws was taken as 1000, considering previous the studies (Kaya and Topal 2015; Ansari et al. 2018; San et al. 2020) The initial velocity was taken as 0 m/s regarding the location of each block and the characteristics of the study area (discontinuities, geometry, etc). Besides, average friction angle value was taken as 44°. The tangential (Rt) and normal (Rn) restitution coefficients of limestone were taken as 0.255 ± 0.45 and 0.65 ± 0.10 , respectively. In this study, tangential and normal restitution coefficients could not be calculated directly with back analysis due to the proximity of the investigation of slope to the road. However, restitution coefficients and friction angle values in limestone rocks around Zonguldak were calculated by Geniş et al. (2017) and Keskin et al. (2020) before. In this study, the means of the values (restitution coefficients and friction angle) obtained from previous studies were used. On the other hand, joint roughness coefficient was taken as 4 according to ISRM (2007). In the analyses, the falling conditions of blocks of different masses (10, 100, and 500 kg) was investigated to reflect the conditions in the study area.

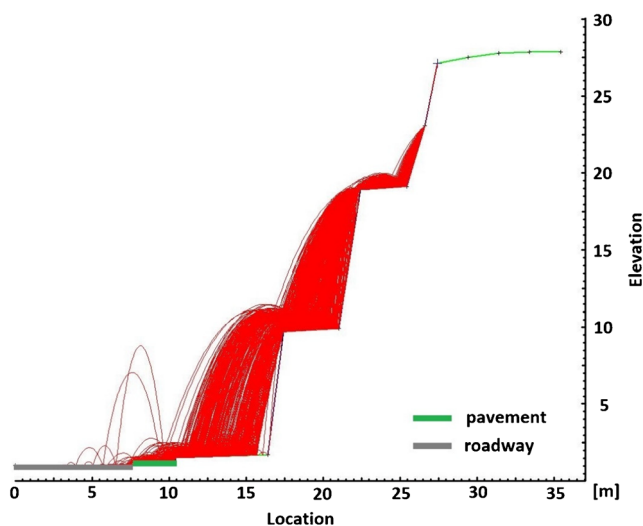


Fig. 7 Rockfall trajectory for 100 kg block on A-A' section

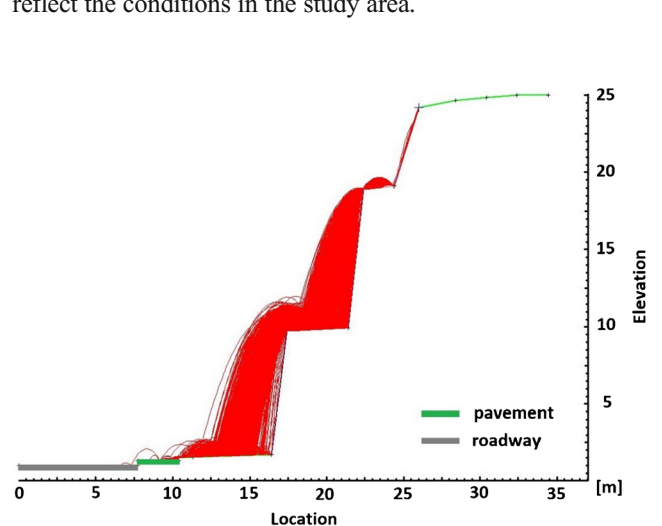


Fig. 8 Rockfall trajectory for 100 kg block on B-B' section

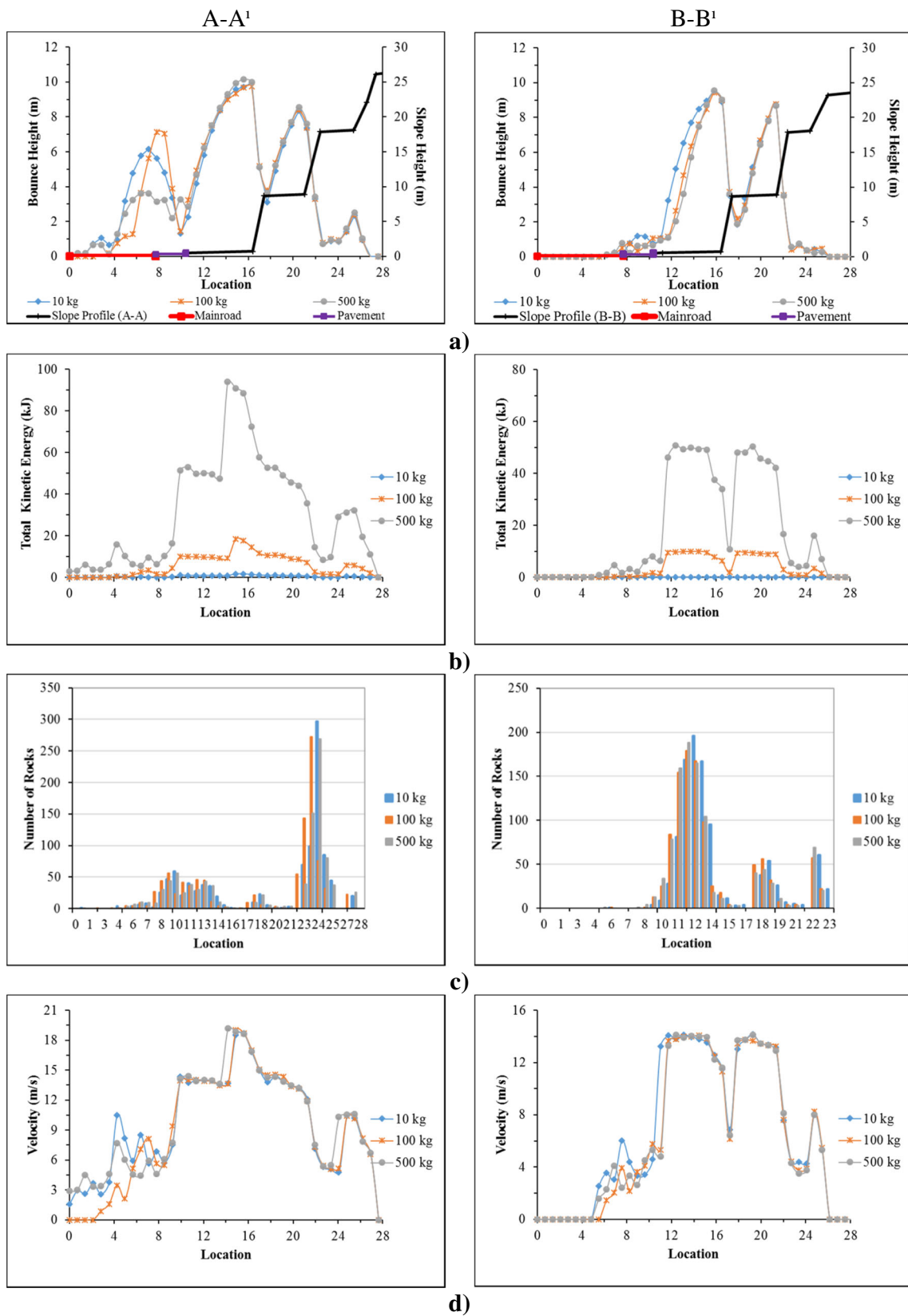


Fig. 9 The analyses result of blocks **a** bounce height, **b** total kinetic energy, and **c** number of rocks and **d** velocity

Table 5 Parameters, ratings, and weights for evaluating the preliminary state of activity (Ferrari et al. 2017) and cases scores for in this study

Parameter	Description	Rating	Weight	Score	
				A-A ¹	B-B ¹
Fracturing degree	Massive rock mass structure	0	3	3	3
	Blocky or very blocky structure	1			
Undercutting	Homogenous weathering	0	2	2	2
	Differential weathering	1			
Block sliding	Block sliding is unlikely	0	2	0	0
	Block sliding is likely	1			
Block toppling	Block toppling is unlikely	0	1	0	0
	Block toppling is likely	1			
Slope performance	Good (close to slope design)	0	3	0	0
	Bad (deviation from slope design)	1			
Total				5	5

Rockfall analyses performed in both sections (A-A¹ and B-B¹) for a 100-kg rock sample are shown in Figs. 7 and 8, respectively. In the 2D rockfall analyses performed with Rocfall (v.4.0), the bounce heights of the blocks, kinetic energy (intensity), and run out of distances values for each section profile were determined (Fig. 9). As a result of analyses for rock blocks with different masses are summarised in Table 4.

In the analysis for both profiles, the number of boulder blocks thrown was limited to 1000. For A-A¹ section, the maximum kinetic energy values of 10, 100, and 500 kg blocks along their motion trajectory were determined as 1.8, 18.4, and 93.9 kJ, respectively. Besides, considering the B-B¹ section profile, maximum kinetic energy values for all three cases were determined as 1.0, 1.0, and 50.7 kJ, respectively.

The number of rock blocks falling on the roadway and pavement road area is around 50–55 for A-A¹ section. The distance between the bottom of the slope and the pavement is 6 m. The maximum kinetic energy of the rock blocks falling to the bottom of the slope was 50 kJ and the energy of the blocks reaching the pavement has decreased to 20 kJ. The bounce height of the rock blocks with a mass of 10 and 100 kg was 10 m between the bottom of the slope and the pavement, and this value was 1.5 m between the pavement and the road. As the mass of rock blocks increases, their kinetic energy values were increased and therefore the bounce heights were decreased. On the contrary of A-A¹ section, the height of the slope in the B-B¹ section was less therefore, the kinetic energies of the fallen rock blocks were relatively less.

In rockfall simulations, 10 of the 1000 fall made for the B-B¹ section have been reached to the pavement. Most of the falling blocks have complemented their movement between the bottom of the slope and the pavement. While the kinetic energy of the blocks with a mass of 500 kg falling was 50 kJ, the kinetic energy of the blocks that could reach the pavement has decreased to 5 kJ. In this case, only a few blocks with different masses were able to reach the road and their kinetic energy remained around 0.5–1 kJ.

In the rockfall analysis, the falling rock blocks has generally finished the pavement for both sections and even movement trajectories in the A-A section have reached the roadway. This situation was confirmed in the field with observations of the occasionally rockfall incident too.

Rockfall risk assessment

It is very important to assess the risks of rockfall that may occur in main roads and settlement regions (Budetta 2004). For this purpose, rockfall risk assessment systems have been developed by several researchers over recent years (Pierson and Van Vickle 1993; Lateltin et al. 2005; Pack and Pack 2006; Russell et al. 2008; Saroglou et al. 2012; Ferrari et al. 2017).

In the assessment of rockfall hazard potential of the study area by Ferrari et al. (2017), the Evolving Rockfall Hazard Assessment (ERHA) system was used. ERHA is a new assessment method that proposed by the revising of the Swedish code, which is the most used assessment method in rockfall

Table 6 Identification of the final class of the state of activity (Ferrari et al. 2017)

Preliminary score	Preliminary class	Without signs of activity	With signs of activity
0–3	Low	Low	Medium
4–7	Medium	Medium	High
8–11	High	High	High

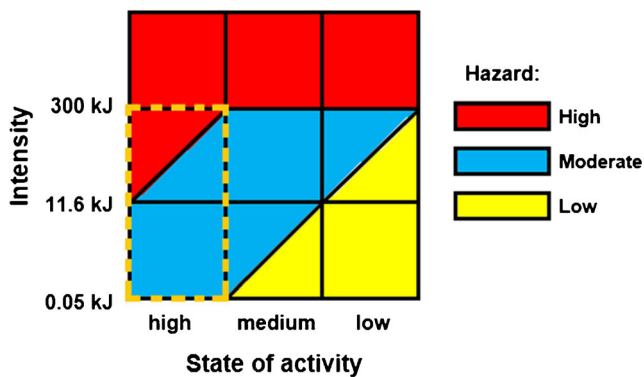


Fig. 10 Hazard classification of ERHA (Ferrari et al. 2017) and hazard levels of the cases in this study are shown in the dashed line area

risk assessments. The assessment system was developed to evaluate possible rock falls in open pit coal mines by identifying hazardous areas along the slope. Rockfall intensity (kinetic energy) and state of activity criteria are the two basic parameters of the assessment system.

State of activity is based on a scoring basis, which is calculated by considering the geological structure, potential instability mechanisms, and the slope state. These features can be observed and scoring quickly (Table 5) and provides a lot of convenience in terms of the evaluation system. The scoring system was defined according to the importance of each parameter in the hazard assessment in Table 6; the final state of activity is described, taking into account the existence of activities related to rockfall. The preliminary class of state of activity increases by one class in the presence of at least one of the signs of activity, such as recently recorded rockfall events, fresh unweathered surfaces, and obvious voids on the wall (Ferrari et al. 2017).

Within the scope of this study, the calculated scores were evaluated in Table 6, and the state of activity status is determined for the study area. For this purpose, firstly, the fracturing degree was rated 1 because of the three sets of joints on the slope surface. Thereafter, in detailed measurements on the slope surface, it was determined that there was a differential weathering condition. The slope performance parameter has been taken good (close to slope design). As a result of the assessment, the state of activity score was determined as 5 for both profiles. For both slope profiles, the obtained scores

correspond to the “medium” state of activity class. However, for the study area, the state of activity class is defined as “high”, taking into account the previous rockfall activities. Therefore, considering that the state of activity class is the same in both profiles, rockfall intensity values obtained from the analyses stand out as the main variable in the ERHA risk assessment.

Rockfall intensity is a parameter that depends on the mass of an unstable block, initial position, and the energy distribution along the path. Besides, intensity is characterized by the kinetic energy that the falling block could reached (Ferrari et al. 2017).

ERHA assessment system consists of a matrix in which the state of activity and intensity (kinetic energy) is considered. There are five different hazard classifications according to the matrix given in Fig. 10 and the possible hazard levels of rockfall increases in proportion to its intensity. The moderate to high hazard level (blue-red zone) indicates that medium intensity and high state of activity may be expected. The moderate hazard level (blue zone) means medium/low rockfall intensity and medium/high state of activity area. The low to moderate hazard (yellow-blue zone) indicates medium/low intensity and medium state of activity. Further investigations are recommended against the possibility of rockfalls that may occur in both the blue-red and yellow-blue zones. The low hazard level (yellow zone) defines the low rockfall intensity and state of activity, and there is no possibility of a very serious rockfall in this zone (Ferrari et al. 2017). In addition to classification matrix shown in Fig. 10, the hazard levels in the studied cases are indicated with the dashed line area.

In this study, considering the intensity values obtained from the rockfall analysis on two different profiles and the state of activity class defined according to Tables 5 and 6. Accordingly, in the risk assessment considering the blocks with different masses from the slope surface, the risk hazard level of 10 and 100 kg rock blocks was determined as “moderate”. However, in the evaluations on rock blocks with a mass of 500 kg, it was concluded that the risk level could into two categories as “high/moderate” (Table 7).

According to the ERHA risk assessment, the rockfall potential was determined as moderate and high for study area. Consequently, this situation has been revealed that dangerous

Table 7 Risk assessment of the study area according to the ERHA method

	Mass of the falling block (kg)	Preliminary activity class	With sign of activity	Risk
A-A'	10	Medium	High	Moderate
	100	Medium	High	Moderate
	500	Medium	High	High/moderate
B-B'	10	Medium	High	Moderate
	100	Medium	High	Moderate
	500	Medium	High	High/moderate

for pedestrians and passing vehicles on the side of the road. The studied slope geometry has two steps, a total height of 18 m, and a slope of 70–80°. The characteristics of the slope and having residential areas on upper bench of the slope have been restricted the measures that can be taken. In this scope, barrier and steel mesh application was suggested as a protective measure in the study. Thus, it is aimed to prevent serious fatalities and damage that may occur due to rockfall. In the analyses according to the maximum kinetic energy value, it was specified that the use of a barrier with a capacity of 200 kJ may be sufficient. On the other hand, considering the bounce heights of the rock blocks, the barrier height was taken as 3.0 m.

Conclusion

In the Zonguldak region, large rock falling activities are encountered in the rocks dominated by limestone rocks. The tectonism of the rock units, discontinuities, and rainfall conditions of the region increase the possibility of rockfall potential. In this study, the potential of rockfall on the slopes of Zonguldak-Kozlu main roadway was investigated. The investigation carried out in the study area indicates that rockfall phenomenon may occur. In detailed field observations on scanline survey, it was determined that it contains mainly two discontinuities sets and one bedding plane on the rock mass. On the other hand, laboratory studies have indicated that the rock unit is very high strength class.

In this present study, rockfall analyses were performed out on two slope profiles by using the Rocfall (v.4.0) which is the 2D numerical software program. The average block sizes measured during scan line survey on the slope surface have been used in 2D analysis. The bounce height, total kinetic energy, number of rocks (rock-end points), and the velocity of the rocks were analysed for each selected profile. In this study also, rockfall risk assessment was evaluated according to the Evolving Rockfall Hazard Assessment (ERHA) method. According to the ERHA method, which is an evaluation system for the state of activity and rockfall intensity of the rock mass, the hazard level along the slope was determined as moderate for 10 and 100 kg fallen blocks. However, in cases where a 500-kg rock block has fallen, the risk level has been determined as high/moderate. As a result, this study has determined that transportation (traffic and pedestrians) safety is threatened due to rockfall events. Besides, it should be taken into consideration that a serious rockfall event on the slope between Zonguldak and Kozlu may cause the main road to be blocked. The last rockfall incident that took place in the study area on March 26, 2021, has also revealed this situation. Consequently, catch barrier with specified height and energy capacity and wire mesh application on the slope surface are recommended to prevent possible losses.

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Declarations

Conflict of interest The authors declare that they have no competing interests.

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