ORIGINAL ARTICLE

Evaluation of rock falls in an urban area: the case of Boğaziçi (Erzincan/Turkey)

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Abstract Disasters caused by events such as earthquake, flooding, rock falls, landslides are often encountered. However, generally, the reasons for the destructive and devastating effects of these nature events are that settlement locations were chosen without site investigation studies, or that available studies were inadequate. Such inadequacies in the field are related to inappropriate settlement location and the resulting damage caused by rock falls. This study evaluated rockfall risk in a settlement that developed in a similar manner. The study was carried out in Boğaziçi village of Kemah (Erzincan/Turkey), which is located in a very important tectonic zone. The study site is located on the lower sections of an area with very steep cliffs and 50–75° slopes. This cliff, which is the source of rockfalls, has a slope dip of approximately 90°. The cliff comprises 25–30 m high, fractured and cracked basaltic volcanic mass. To determine block size in the study area, scanline survey measurements and block size measurements were performed on blocks that loosened and fell from the cliff face. It was found that block sizes reached 6 m^3. Rockfall analyses were performed along the selected profiles using the Rockfall V.4.0 software. Kinetic energy, bounce height, horizontal location of rock end-points, and velocity of the rocks along each section were evaluated separately for each profile. This data were used to produce distribution maps for each profile and the settlement was evaluated in terms of rockfall risk. The results indicate that the study area was at risk of future rockfalls and that it would be appropriate to relocate one part of the settlement.

Introduction

Disasters caused by flooding, rock falls, landslides, etc. are common. However, generally, the reasons for the devastating effects of these natural phenomena are that settlement locations were chosen without field studies were conducted, or that available studies in the related field were inadequate. According to World Bank data, 95 % of deaths due to natural disasters occurred in developing and underdeveloped countries (Kremier and Arnould 2000). The damage caused by rockfalls is caused by inadequate evaluation of geological data or improper location selection. Therefore, geological and meteorological aspects should be investigated, in order to assess risk at existing and proposed settlement locations and to reduce the potential damage resulting from such natural events.

Rockfalls refer to the movement of loosened rock blocks on steep slopes under the effect of gravity by free fall, rolling down the slope, and/or bouncing. Blocks may be dislodged due to a combination of factors such as joints, freeze–thaw, root growth and water ingress, or by natural events such as earthquakes (Ritchie 1963; Varnes 1978; Hutchinson 1988). This movement may cause significant damage and loss of life as the blocks move very rapidly. Compared to other mass movements, although rockfalls have smaller volumes, they have highly destructive effects (Evans and Hungr 1993). In addition to earthquakes, urban and rural settlements in some regions may experience losses caused by landslide, flood, rockfall, etc. Previous studies of natural disasters in Turkey within the last 50 years reported that rockfalls were responsible for a

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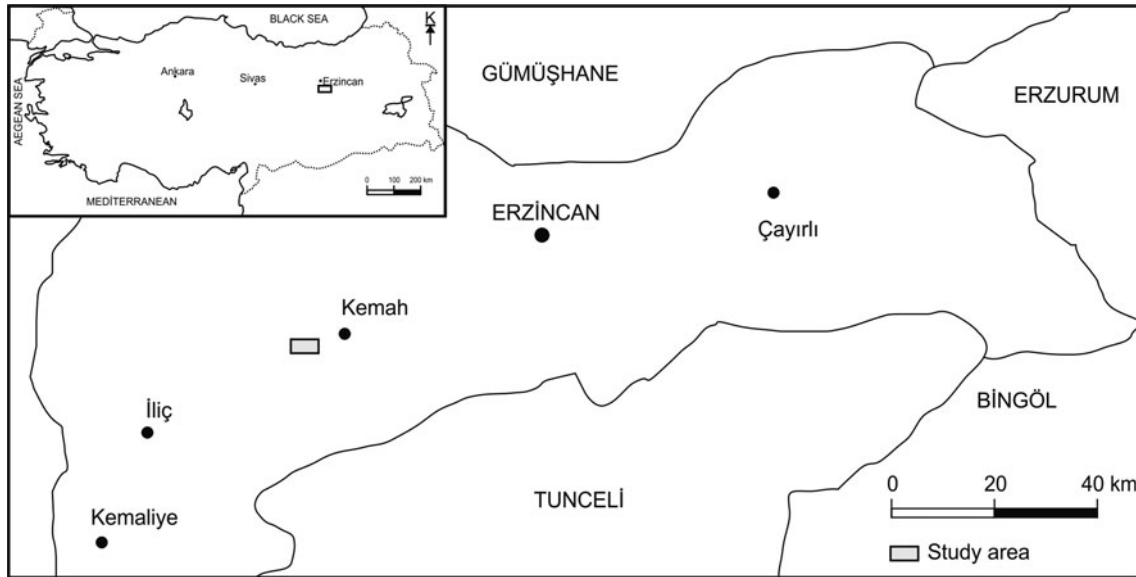Karabük University, 78050 Karabük, Turkey
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Fig. 1 Location map of the study area

Fig. 2 Active faults in the vicinity study area (NEMC 2012). **a**, **b** Locations of earthquakes occurred in the vicinity of the study area between 1988 and 2011
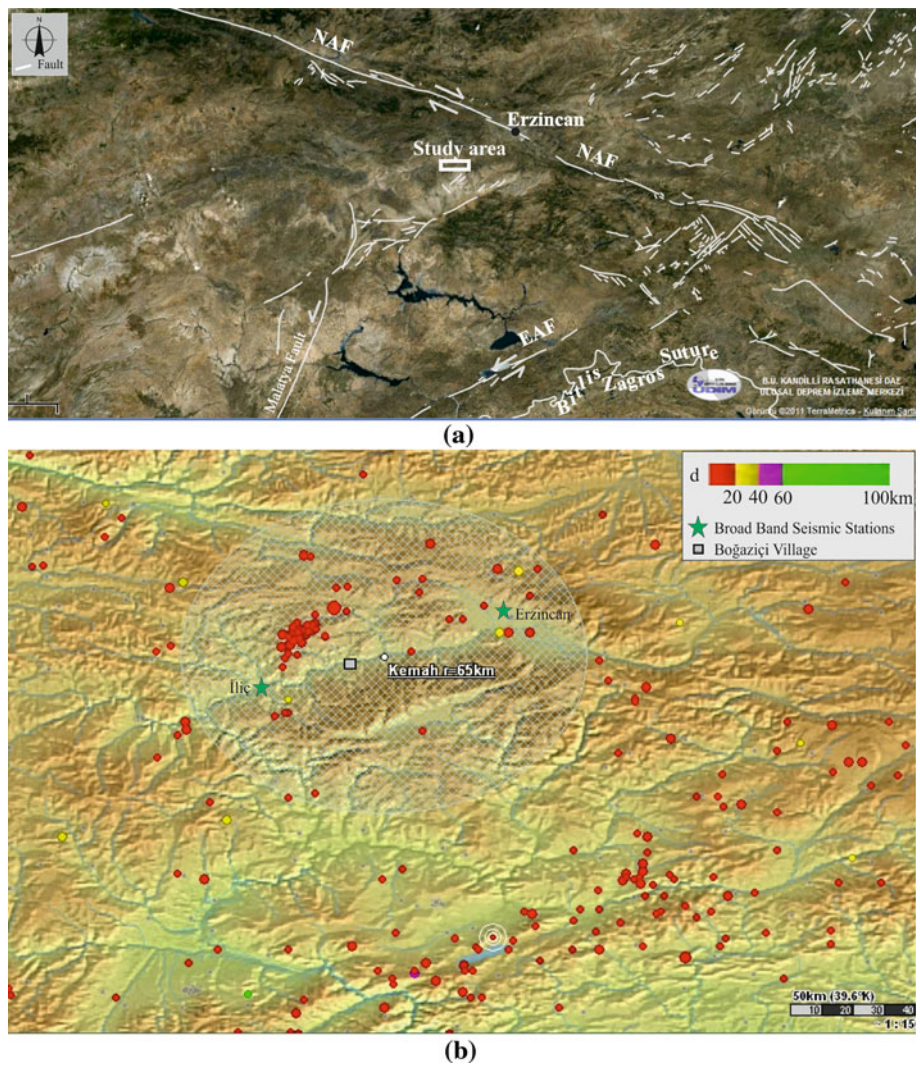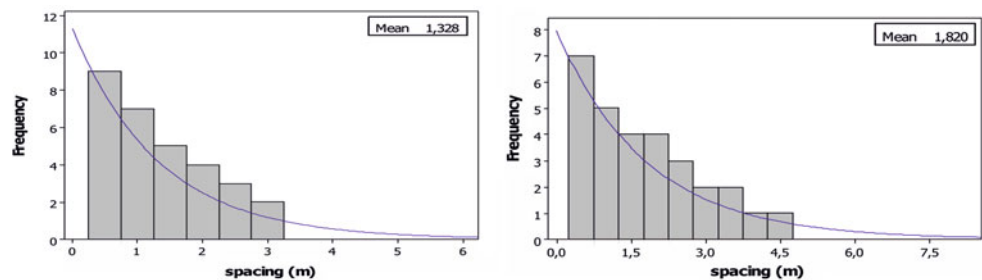

(a)

(b)

Fig. 3 Photos showing slopes and general view of the study area

Fig. 4 Views from a scan line survey

significant proportion (8.26 %) of disaster victims (GDDA 2006). It is therefore important to determine the behaviors of blocks with the potential to fall on settlements located on steep slopes.

This study examined rockfall risk in a settlement that lacked modern location principles and which had previously experienced several rockfalls (Fig. 1). In order to perform computer-assisted rockfall analyses, initial velocity (which controls the movement of the rock block), the shape and weight of the block, the properties of the slope, and the material composition of the slope should be identified (Giani 1992; Dorren 2003). The trajectory that a falling block will follow, falling velocity, bounce height, and kinetic energy can be identified by computer-assisted rockfall analyses (Schweigl et al. 2003; Yılmaz et al. 2008; Tunusluoğlu and Zorlu 2009; Binal and Ercanoğlu 2010). The identification, through field observations, of slopes with potential rockfall risk has a specific importance in rockfall analyses. Within the scope of the present study, a sophisticated field study was conducted. Rockfall slope profiles and the sizes of previously dislodged blocks were measured in the region. Simulations were designed to

Fig. 5 Discontinuity spacing histogram

Fig. 6 Fallen rock blocs showed in the study area

identify initial velocity of these rocks and geological discontinuities in the source rock.

Geological and geomorphological features of the study area

The study area was located near the intersection of the North Anatolian fault line (NAF) and East Anatolian faults line (EAF), which are the two most important fault lines in Turkey. This region between the NAF and EAF constitutes the easternmost tip of the Anatolian plate and is among the regions with the highest active fault concentration (Fig. 2a). The map in Fig. 2b shows the locations of earthquakes greater than three magnitudes that occurred in the vicinity of the study area between 1988 and 2011. The region is highly active in terms of earthquakes and so local

settlements may be at potential risk from rockfalls. Discontinuities involved by earthquakes and rock mass were reported as factors that prepare or trigger rockfalls (Zellmer 1987; Kobayashi et al. 1990; Bull et al. 1994; Chen et al. 1994; Vidrih et al. 2001; Marzorati et al. 2002; Dorren 2003). Statements from local people indicated that a major rockfall disaster occurred in 1992 (during the Erzincan earthquake), killing several people and causing material loss in many households.

The village that observed intense rockfall threats located in the south west of Kemah (Erzican, Turkey; see Fig. 1). Boğaziçi village is approximately 66 km away from Erzincan, 16 km away from Kemah. The village is located just north of the Fırat River that one of Turkey's most important rivers. The altitude values of study area vary from 996 to 1,132 m. The northern parts of the study area have almost steep topography. Boğaziçi village is located

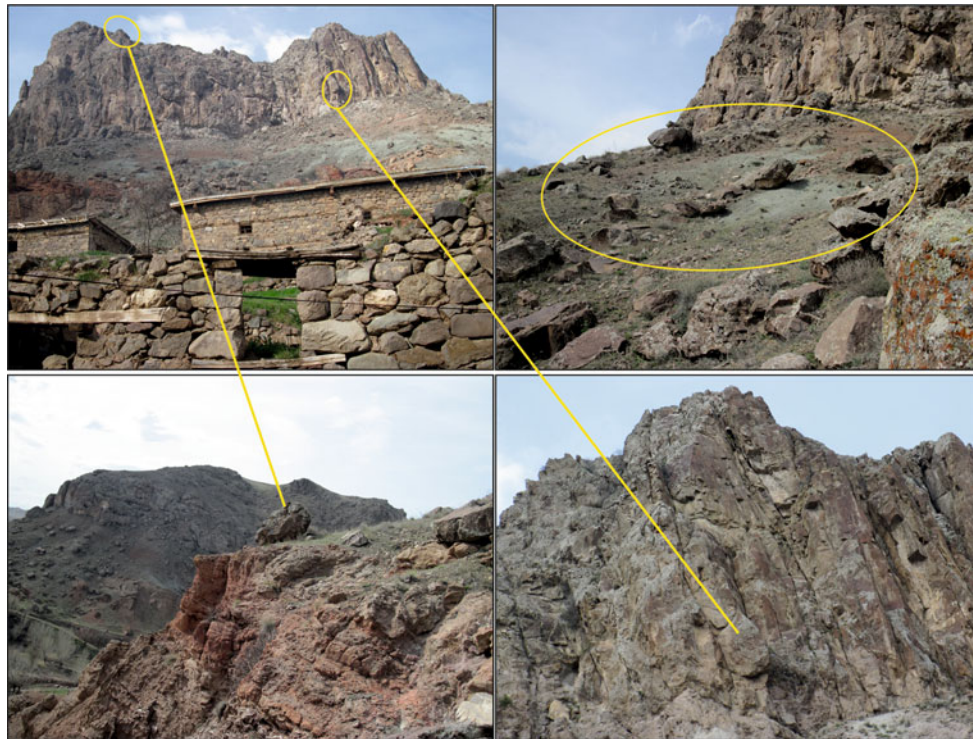**Fig. 7** Profiles used in the rockfall analysis
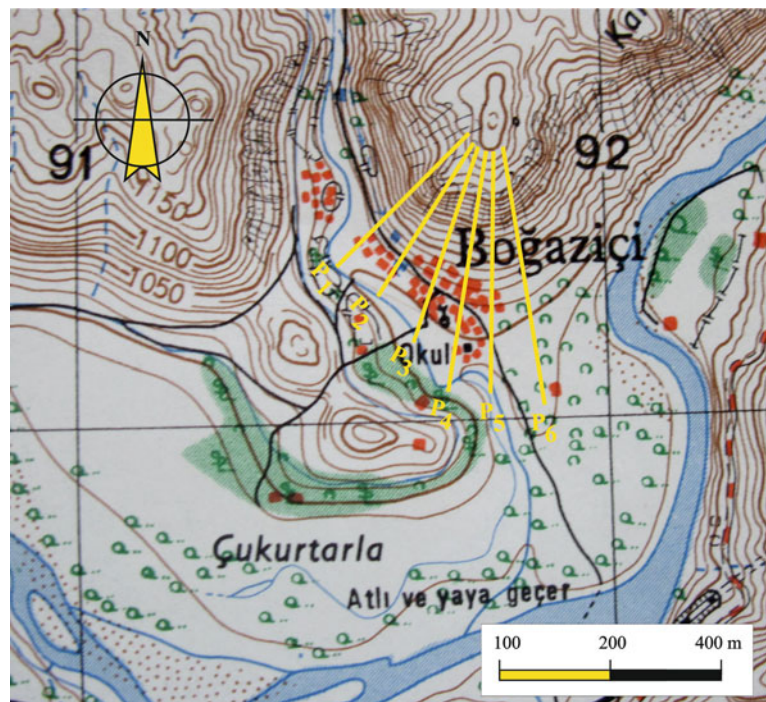
Fig. 8 Photos showing potential rockfall areas in the study area

below a very steep cliff that is the source of rock falls. The cliff has a slope of 90° in some places and a height of approximately 25–30 m; it is composed of highly fractured and cracked basaltic volcanic. It was observed that there were loosened blocks at some places on the 50–75° slopes facing toward the village. These blocks sometimes present a danger for the village (Fig. 3).

Properties of rock mass

Discontinuity properties of the rock masses in the study area that influence the risk of rockfalls were identified using the scan-line survey recommended by ISRM (2007). Line surveys with a total length of 62 m were performed in the study area and the characteristics of the discontinuities on the slopes were determined (Fig. 4). The DIPS software program was used to generate the stereonets from the scanline survey data collected. Based on these analyses, it was revealed that two major joint sets were identified in the cliffs. The orientations of these sets were found to be 79/210 and 84/156.

According to data obtained from scan line surveys, the apertures of the discontinuities ranged between 2.5 and 10 mm and were not filled with any organic or geological material. The range of discontinuities was also measured in the study area and statistical analyses were conducted. Analyses showed that the variations of the discontinuity spacing (Fig. 5) display negative exponential relationship, which is in good agreement with Priest (1993). Mean

Table 1 Dip direction, spacing of identified discontinuity sets, and volumetric number of discontinuity

Scan line (m)	J1	J2	J1 Spacing (m)	J2 Spacing (m)	Jv (n/m^3)
62	79/210	84/156	1.32	1.82	1.30

discontinuity range was 1.32 m for 79/210 discontinuity; and 1.82 m for 84/156 discontinuity. The persistence of these discontinuities was greater than 20 m and were mostly terminated by another discontinuity. To determine block sizes of the discontinuities in the study area, volumetric joint count (Jv) was calculated, as specified in ISRM (2007), as shown in Table 1. Volumetric joint count (Jv) is a relative expression of block size and expresses the total number of discontinuities observed in a rock mass in unit volume. The discontinuities in the study area were defined as "large blocks" based on the volumetric joint count (ISRM 2007). In addition, block size measurements were conducted inside houses destroyed by previous rockfalls and for blocks suspended on the local slopes. It was found that average block size was 2–2.5 m^3; however, there were blocks of up to 6 m^3 (Fig. 6).

Rockfall hazard analysis

In the present study, in order to determine rockfall risk in Boğaziçi village (Erzincan-Turkey), rockfall analyses were
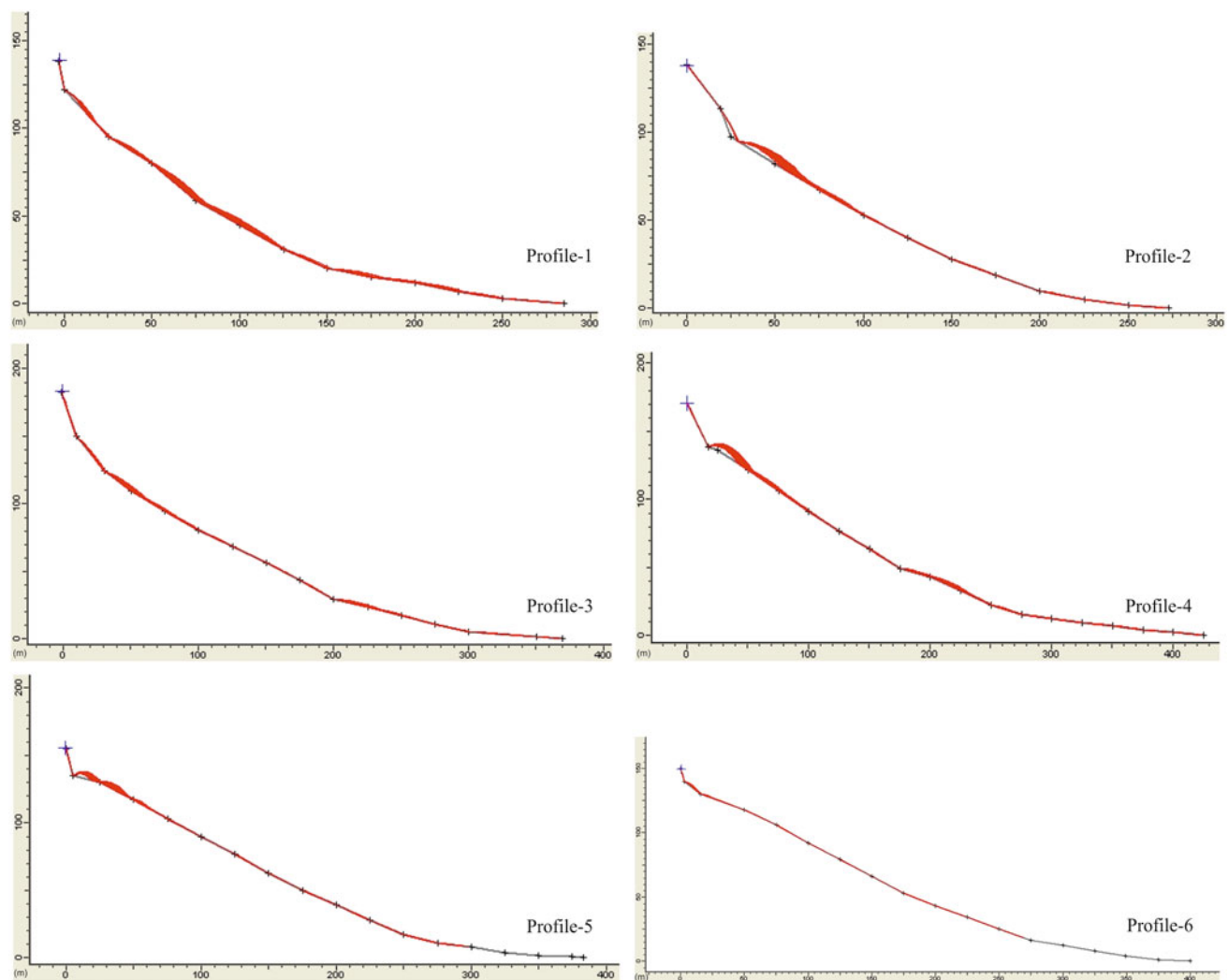
Fig. 9 Trajectories of the analyzed profiles with rockfall potential

performed in six profiles (Fig. 7) using the RocFall V.4.0 software (Rocscience 2002). RocFall is a useful computer program based on the laws of motion and collision theory, which allows the path of rock blocks to be calculated. The kinetic energies, velocities, end points (fall out distances), and bounce heights at each point within a profile can also calculated. RocFall can also assist in determining remedial measures: the material properties of each slope segment can be changed and the analysis re-run, comparing the results. The program produces three "envelopes": the kinetic energy envelope, the velocity envelope, and the bounce height envelope. Boğaziçi village was settled without a scientific evaluation of local rockfall risk. While selecting the slope profiles used in the analyses, we paid attention that these profiles comprised the entire village settlement and were adequate to identify rockfall risk in the settlement. The field studies identified two different source regions for rock falls, consisting of the cliffs with a height

of 35 m and slope of approximately 90°; and the deposits formed by previously displaced rock masses remaining on the slope (Fig. 8).

The Rockfall V.4.0 (Rocscience 2002) software used in the analyses produces different surface definitions controlling horizontal and vertical coefficients of normal and tangential restitutions that control energy absorption at the contact points of the falling block according to the topography. These definitions include asphalt, bedrock outcrops, clean hard bedrock, talus cover, soil with vegetation, and talus with vegetation. In the present analyses, the surface was defined as "bedrock outcrops". Friction coefficient is also an input parameter, and varies between zero and the main friction coefficient of the block material. In the analyses, a smaller value was selected in terms of main friction, depending on block shape; and as zero for round-shaped blocks. Block weights along the surveyed profiles were found to be between 5,750 and 290 kg, based on
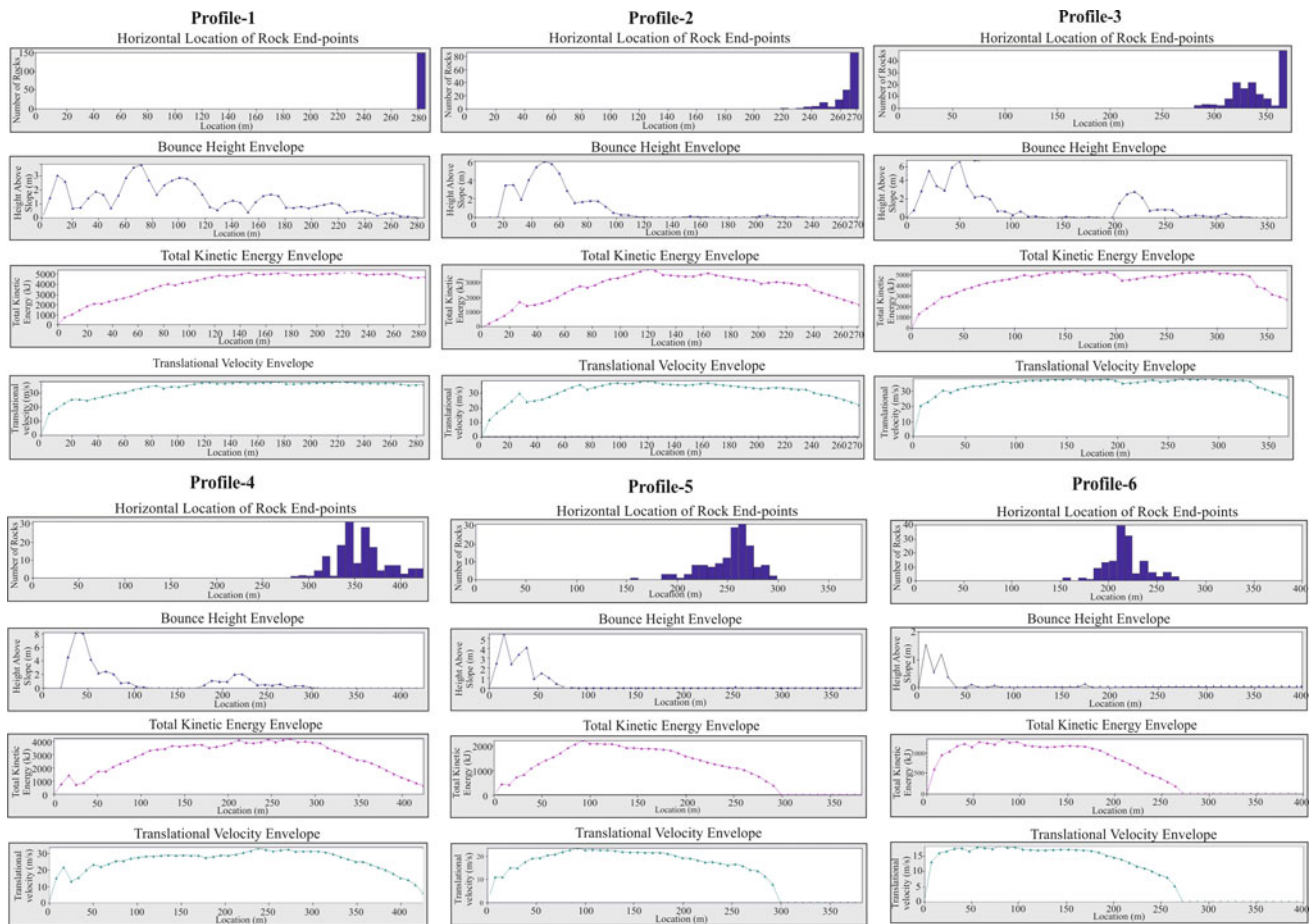
Fig. 10 Defined slope and horizontal location of rock end point, bounce height, translational velocity, and total kinetic energy envelope

block sizes and average basaltic volcanic density. The horizontal and vertical velocities of the blocks were considered as 0 m/s due to their locations (Table 2). Based on these input parameters, the areas of highest potential rockfall risk in the study area were determined. Rockfall trajectory of profile is given in Fig. 9. The output of the analyses (location of rock end points, bounce height, kinetic energy, velocity and graphs of the envelopes) for each profile is presented in Fig. 10. Blue histogram in Fig. 10 shows density locations and maximum point at horizontal axis of analyzed falling blocks. This histogram suggested that majority of the falling blocks move considerably to forward in profiles.

According to the results, a rock falling from the source region along these six surveyed lines would travel a distance of 156–425 m, indicating that the rockfall zone includes the site of the village. In addition, if the energy of the rocks is not dissipated after their fall, they will continue moving by bouncing. Analyses showed that some of the falling rocks might bounce up to heights of 7.8 m at some locations. These data show that falling blocks travel further than the currently abandoned houses that were destroyed

Table 2 Parameters used in the rockfall analysis

Parameters	Value
Minimum velocity cut-off (m/s)	0.1
Friction angle (degrees)	30 ± 2
Number of throws	150
Coefficient of normal restitution	0.35 ± 0.04
Coefficient of tangential restitution	0.85 ± 0.04
Slope roughness	2
Initial velocity (m/s)	0
Sampling interval	50

during previous rockfalls (Fig. 11), and may reach the inner sections of the settlement. Another important factor in rockfalls is the energy of the falling rock. Changes in the kinetic energy of the rocks were also calculated. It was found that the energy of the rocks reached 3 million J even at a horizontal distance of 350 m from the cliff. Furthermore, velocity (maximum 53 m/s) values were obtained in some locations. When considering the velocity of falling boulders, it is nearly impossible for people to shift away to

Fig. 11 Houses destroyed during the earlier rock fall

avoid boulders falling toward them. To avoid the consequences of rockfall events, barriers were considered in the rockfall analyses as protective measures. Rockfall analyses were repeated for the protection barrier height calculations based on the non-elastic barriers that represent the worst

Table 3 Maximum barrier height suggestions for the profiles

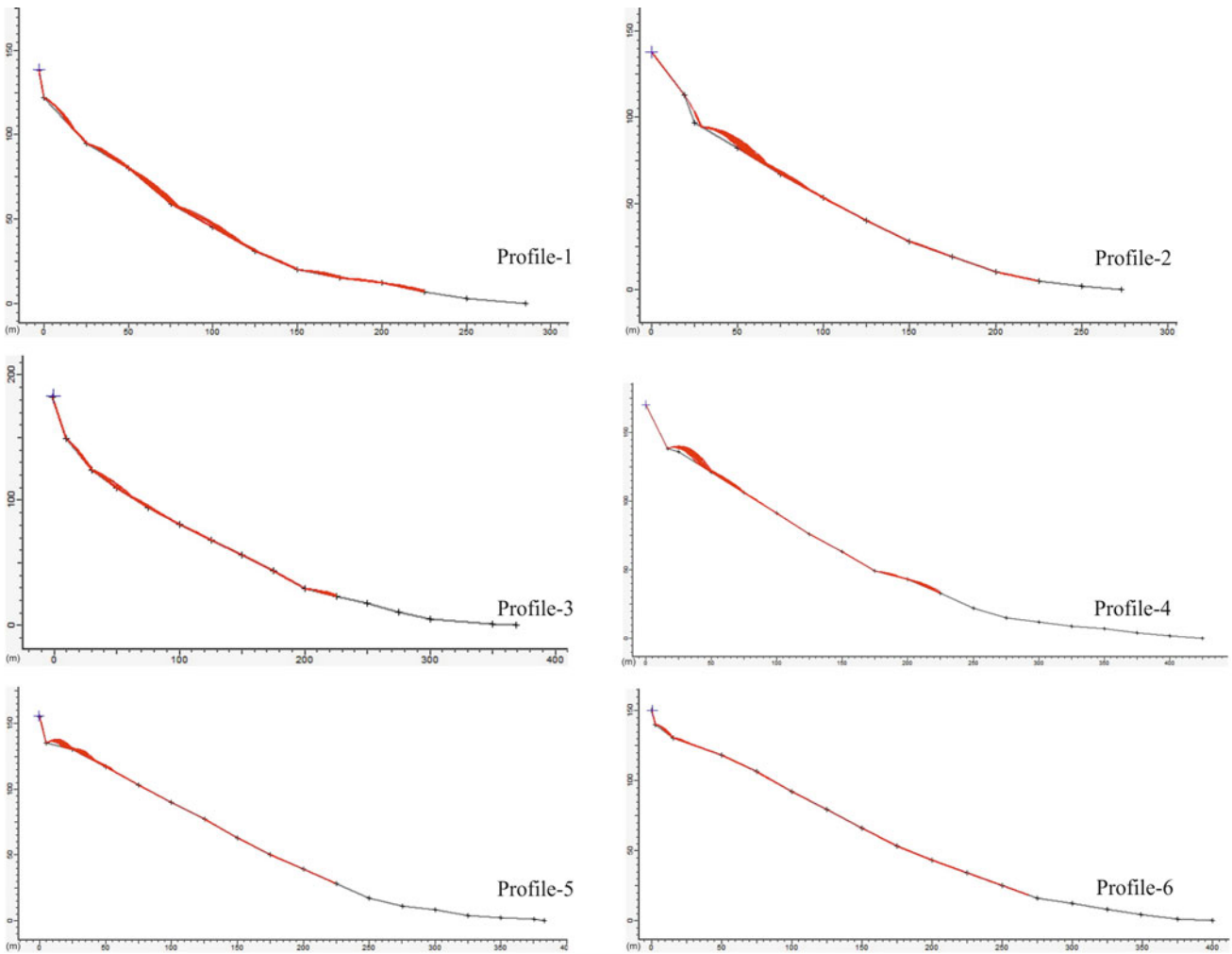| Profile number	Maximum barrier height (m)
1	0.8
2	0.2
3	1.1
4	1.3
5	0.2
6	0.2

Fig. 12 Rockfall trajectories of the profiles with the barrier protection

conditions and located at the edge of the house in village. The maximum barrier heights were determined to be between 0.2 and 1.3 m (Table 3). These barriers were placed to the most suitable areas, having minimum bounce height and kinetic energy, behind of all the houses in the settlement. The barrier heights enough to hold falling rocks were calculated using RocFall 4.0 software. According to the results of these tests obtained from the simulation results, this barrier height which is inexpensive, will be sufficient to protect transportation and human lives when considered with respect to the cost/benefit issues. The rockfall trajectories with these preventive barriers were also shown in Fig. 12. Considering that the houses in the study area were constructed using old construction techniques, such an impact would destroy the walls of many houses in the area. By using the results obtained from rockfall analyses, location of rock end points, bounce height, translational velocity, and kinetic energy distribution maps for study area were produced (Fig. 13). ArcGIS (2005) was used to prepare distribution maps of the data obtained from rockfall analyses. These maps were digitally and cartographically produced. These maps were overlapped with the settlement in the study area, which confirmed that the settlement is at risk from rock falls.

Fig. 13 Zoning maps of location of rock end points, bounce height, translational velocity, and total kinetic energy for the study areas
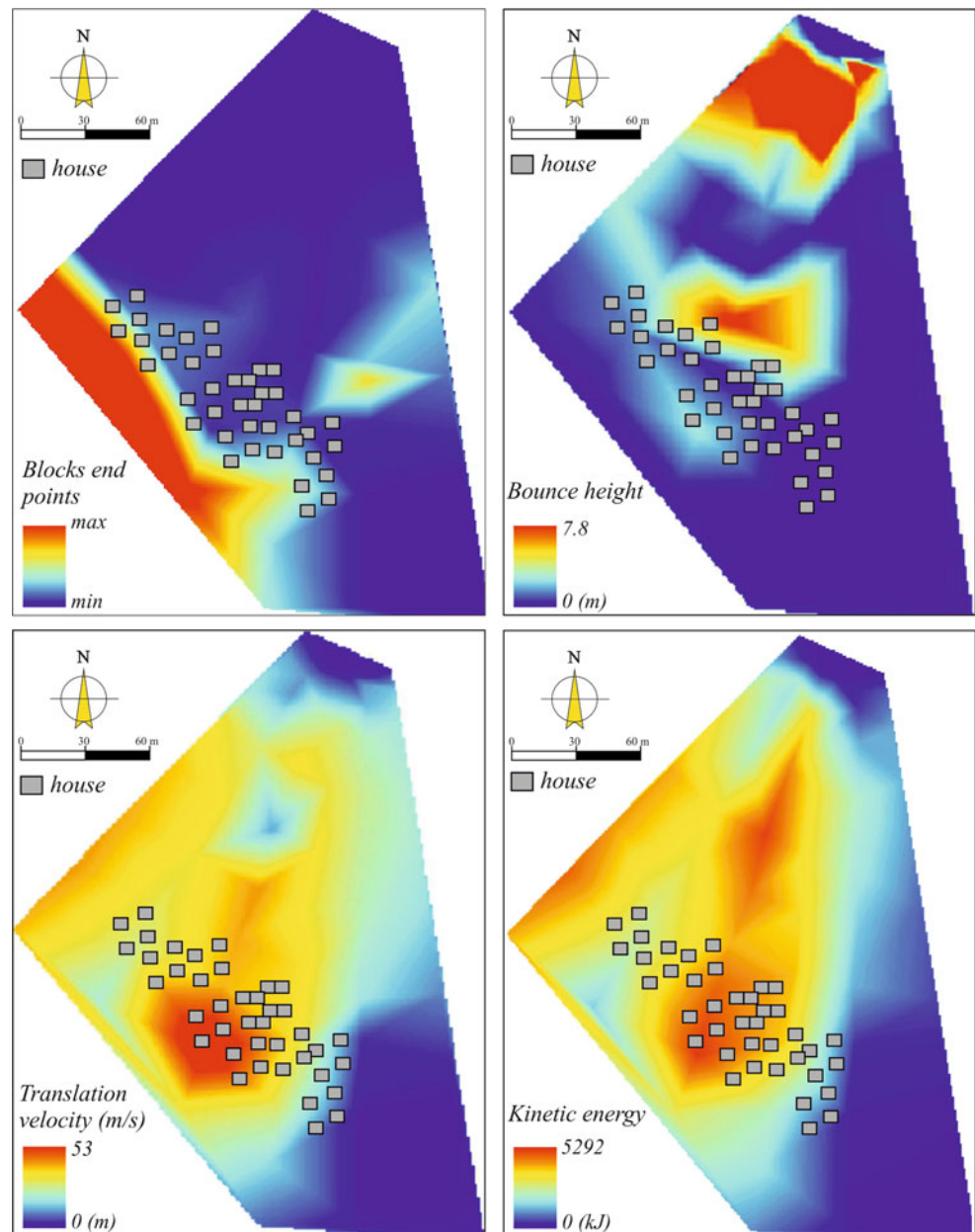
Results and conclusions

The rockfall analysis performed in the present study aimed to determine the geological risk in a settlement that developed without adequate geological knowledge and modern field studies. As understood in the study, this settlement is located in an area of very high seismic activity. Although the adjacent slopes were very steep, the settlement was located below the fractured and cracked rocks and experienced several rockfall events during its history. Rockfall analyses performed in the study confirmed that the area remains at risk from rockfalls, and that some blocks in the vicinity have the potential to travel further into the main part of the settlement than previously damaged houses on the perimeter. It should be remembered that the economic cost of modern geological surveys in planning of current settlement areas will be much lower than improvement or relocation costs due to natural disasters.

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