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Research Article

Rockfall hazard analysis in the Ganjnameh tourist area, west of Iran

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Abstract

Ganjnameh area is considered an important historical-cultural and touristic place in the west of Iran, seriously threatened by rockfall problems. Attractions of this area yearly attract several thousand visitors from all over the world. Several rockfall events have occurred in the area in the past. Rockfalls occurrences will threaten the life safety of visitors during visiting and surveying of the place. The primary purpose of this research was a preliminary analysis of rockfall potential for the cultural heritage site. For this purpose, an investigation based on three phases was done, which are included: site investigation, laboratory testing, and rockfall simulation. Unstable blocks size, the geometry of slopes, weathering conditions, joint study, and sampling were measured and done during the site investigation phase. Physico-mechanical properties of granite were determined in the laboratory. Total kinetic energy, bounce height, and translational velocity of fallen blocks were determined as rockfall simulation outputs. Based on the obtained result, different mechanisms were found on the left side and right side of the study area. The rockfall problems on the right side could be related to jointing and freezing-thawing action, whereas on the left side, steep slope, weathering, and saturating are the main controlling factors. The results indicated that the footpath between Ganjnameh inscriptions and waterfall, which has a dense concentration of visitors, is subjected to severe problems of rockfall occurrences from both sides, especially the left side. Eventually, for the reduction of rockfall potential and its risk, remedial works are suggested.

Keywords: Ganjnameh, rockfall, site investigation, weathering.

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Introduction

Among landslides, rockfall is one of the most common and dangerous types of slope instability because of its high velocity and destructive energy. Rockfalls happen when rock masses are detached from a cliff face and freely fall under the effect of gravity (Youssef et al. 2015; Blahut et al. 2013) which traverses the path in bouncing, sliding, and rolling motions along a sloped surface with high velocity (Leine et al. 2013; Ferrari et al. 2013). This type of natural hazard can cause serious damage in mountainous regions and threaten human life and the saftery of engineering structures (eg: railways, roads and highways) depending on the falling block's volume and velocity. Therefore, rockfall, in many cases, is known as a natural disaster. Different geological, geomorphological, climatologic, and human effects may contribute to occurring rockfall. Most important of these factors include freezing–thawing cycles (Matsuoka and Sakai, 1999; McCarroll et al., 1998), horizontal and vertical accelerations cause by seismic activities of an earthquake, blasting, movement of heavy earthmoving machine (Ding et al. 2012; Abebe et al., 2010; Dorren, 2003; Vidrih et al., 2001) differential weathering in a sequence of weak and hard rocks (Binal and Ercanoglu, 2010) tree root growing (Topal et al., 2012). Therefore, several parameters can be listed as rockfall triggering factors. Nevertheless, geological, topographical, and climatic factors combined with time determine rockfall occurrences potential of slopes. Process-based models are widely used to simulate rockfall movement modes over slope surfaces. For example, Gigli et al. (2014) used 2D and 3D rockfall simulation models to measure some characteristics of the fallen blocks such as bounce height, rock velocity, and kinetic energy based on rock position along the slope. Ma et al. (2011) simulated actual rockfall using discontinuous deformation analysis, and they have classified rockfall energy losses into three types. s. Topal et al. (2007) used a 2D rockfall model to determine rockfall characteristics in terms of run-out distance, bouncing height, kinetic energy, and rock velocity over several profiles. The results of the simulation were utilized to show the regions at risk. Generally, it can be said that in most rockfall studies, the main aim is reducing the hazard and risk of rockfall occurrences. For reducing the danger of rockfall, the dominant mechanism must be detected, and then by elaborating the significant factor by remedial works, the danger of this phenomenon will be decreased. One of the utilized methods for decreasing rockfall risk, is decreasing risk elements in the rockfall region. Moreover, in many cases, it not possible to reduce risk elements and some protective structures, and remedial works must be employed to protect risk elements against fallen blocks. For the efficient design of the facilities, some characteristics of fallen blocks must be available to help the designers in deciding on the location and capacity of the facilities. This data will be achieved by using computing models such as the 2D rockfall model.

Many environments have the occurring potential of rockfall all over the world. So, several researchers have focused on rockfall analysis using different methods. Granitic terrains have a high potential for rockfall occurrence because of two main reasons. Firstly, the granitic mountains usually have steep slopes and make cliffs due to the high strength of granitoid rocks. Secondly, granitic outcrops normally have three main joints that can generate separated and rockfall prone blocks. Several researchers have studied rockfall hazards in granitic sites (Spadari et al., 2013; Almeida and Kullberg, 2011; Alejano et al., 2010). Previous studies mainly have focused on rockfall analysis along transportation corridors (Vishal et al., 2017; Sing et al., 2016; Wie et al., 2014; Palma et al., 2012). Also, the literature review indicated that rockfall analysis was performed in particular regions as touristic areas to protect and preserve visitors and monuments (Wang et al., 2012; Park et al., 2009; Topal et al., 2007). Binal and Ercanoglue (2010) studied rockfall hazard in the Kula Geopark region and concluded that it is threatened by rockfall. Wang et al. (2012) have performed a preliminary study for assessment of rockfall potential of Shijing Mountains Sutra caves site to help for better design of safe tourist and visitor paths. Their results show that rockfalls threaten the life safety of tourists and visitors of the Sutra caves. Youssef et al. (2015) have performed research work on rockfall hazard at Al-Noor Mountain, using a combination of remote sensing method and field investigation. They found that both the Makkah and Al-Noor escarpment track roads and visitors who use the path to see Hira cave will be affected and damaged by rockfall. Kaya and Topal (2015) Evaluated rock rockfall hazard for an attractive coastal area around Kusadasi in Turkey. Based on their results, rockfall was considered the main dangerous slope instability in this area, and many falling blocks can reach the beach threat people in that location. Dincer et al. (2016) investigated the rockfall hazard potential near the Tatlarin Underground City in Turkey. They show that instabilities are mainly controlled by differential weathering in a sequence of weak tuff and hard basalt. Topal et al. (2012) have carried out a rockfall analysis for a historical site in Kastamonu, Turkey. They found that all directions around the castle have rockfall potential, related to physico-chemical weathering, earthquake shaking, and jointing of sandstone or a combination of the factors.

Hamedan is one of the most historical and tourist cities in the west of Iran. This city has been become the Median capital in the 6th century BC by Cyrus the Great, when the city was known as Ecbatana or Hegmataneh. Hamedan region has impressive natural beauty (Abasabad beauty valley, Alisadr cave as the largest watery cave in the world, Alvand Mountain, Ganjnameh waterfall) and cultural and historical attractive places (Ganjnameh Inscriptions, Hegmataneh Hill, the tomb of Avicenna, Ester's tomb, etc.). Ganjnameh area has natural and historical attractions, and a lot of tourists and visitors yearly travel from all around the world to visit this area. In this place, two inscriptions (Fig. 1a), a waterfall, the route of Alvand mountain climbing, and several entertainments exist. It should be noted that the inscriptions have been caverned in granitic rocks, and the left one was ordered by Darius the Great (485-521 BC), and the right one was ordered by Xerxes the Great (485-65 BC). This area is prone to rockfall hazard. On 17th December 2005, immediately after a heavy snowfall period, a massive rock slope failure occurred on the left side of Ganjnameh. The Ganjnameh waterfall flows down from a height of about 12 m with an average output of about 200 liters/second (Fig. 1b). This waterfall is frozen on most winter days and is known as an ice waterfall, which attracts many visitors during winter. The substantial large volume of rock debris that came to rest on the waterfall had blocked the site entirely and closed for 9 months for rehabilitation works. Because of the very high tourism activity in the area, hazard analysis and proposing suitable preventive methods to provide a safer environment for visitors is the main aim of this study.

Fig. 1: General view of the most important Ganjnameh area attractions. A) Ganjnameh Inscriptions and b) Ganjnameh Waterfall

Study area

Ganjnameh area is located 5km southwest of Hamedan city (Fig. 2). In this research, the study area is limited between Ganjnameh inscriptions and waterfall, where usually high density of visitors is presented in most times. This area was divided into several zones based on similary exposed rocks to better evaluate rockfall susceptibility potential. Ganjnameh waterfall and the left side of the valley is divided into 2 zones (Fig. 3a). Based on these categories, Ganjnameh inscriptions are located in zone 1 of the left side. The valleys' right side is divided into 5 zones between the valley and Alvand climbing track road and 4 parts over the road (Fig. 3b). Ganjnameh area lies on the toe of the Alvand Mountain, which has a mountainous climate with snowy winters. This area is cold, and every year temperature may drop below -30°C on the coldest days. Because of the weather and elevation of the area, heavy snowfall is common during winter, which can persist for up to three months. The climate of Hamedan city is semiarid and approximately 317 mm can be considered as annual precipitation of this area.

Meteorology data during 1976–2011 indicated that in the area, the minimum and maximum temperatures were measured about -32.8 and 40 C^{o} with an average of 136 freezing days per year. From a geomorphological point of view, the hillside of the Alvand Mountains is composed of many valleys affected by various erosion and active tectonic processes in the area. Some evidence, such as the presence of waterfall and seismic events are supported the neotectonic activity of the area. The Alvand batholith, as one of the largest plutonic bodies in the Sanandaj–Sirjan metamorphic belt (SSMB), was located in the west of Iran and consists of gabbro, diorite, tonalite, granodiorite, porphyroid granites, and hololeucocratic granitoids. Porphyroid granites compose the main part of this batholith such as the study area outcrops. Because of high elevation and relatively high precipitation, which is mostly snow, several springs emerge in the Alvand Mountain. The water of these springs was used for irrigation of gardens in the valleys. In terms of vegetation, the area will be divided into valleys with dense vegetation and slope with poor vegetation to naked.

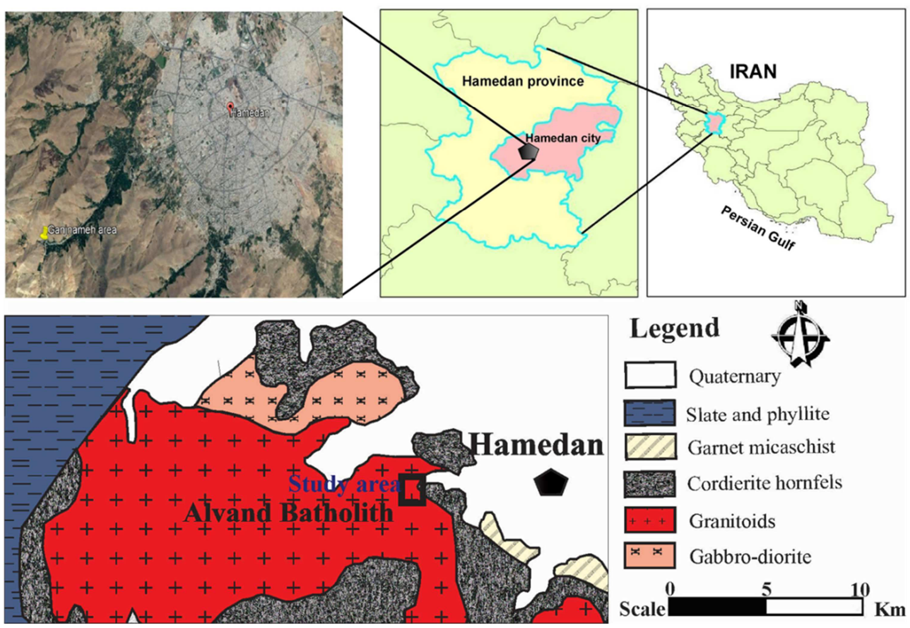

Fig. 2: Hamedan city and location of the study area, geological map of the study area

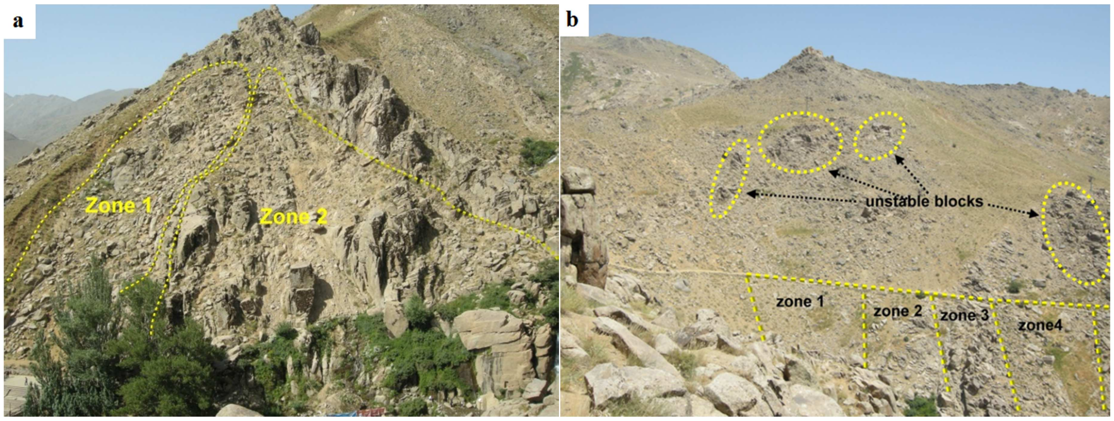

Fig. 3: a) A view of the left side of the study area and its 2 zones. b) General view from right side of the study area

Material and methods

As discussed earlier, this study aims to assess rockfall hazard in the Ganjnameh tourist area. For this reason, a research program has been drawn based on three significant phases, including site investigation, laboratory studies, and rockfall simulation by computing software (Fig. 4). During the site investigation phase, comprehensive field surveying was done to determine the location of unstable blocks, their volumes and geometries, the key areas prone to the rockfall, geometry of slopes, sampling for laboratory works, weathering evaluation, and joint studies. Characterization of discontinuities in the study area was performed based on ISRM (1978) suggested methods. Laboratory investigation was done to determine some engineering geological properties, including petrographic, physical, and mechanical properties. Three thin sections have been prepared and studied using a petrological microscope to determine the mineralogical abundance and textural features of the rocks. Core samples were prepared and physico-mechanical properties have been determined following the standard test procedures suggested by the ISRM (2007). Six tilt-tests with four repetitions were also done on pairs of small slabs to estimate the basic friction angle. A rockfall program was performed and some indices such as total and translational kinetic energy, bounce height, and translational velocity of fallen blocks were determined. Finally, the mechanism of instability was determined and for protection purposes, some methods were suggested.

Results and discussions

Site investigation and engineering geological setting

The study area lies on the Alvand batholith as one of the largest plutonic bodies in the west of Iran. This area was divided into several zones, and a detailed mapping was carried out to identify the unstable blocks and their volumes and locations. Two types of blocks were defined, including potentially unstable blocks and key blocks. The key block was considered a potentially unstable block or block that supported adjacent blocks and loosely led to running the adjacent blocks. Based on the geological mapping, the maximum overall slope face is measured for zone 2 on the left side of the study area. This zone also has the maximum key blocks and can be considered a hazardous zone. The blocks' volume and weight are found in wide ranges from 0.04 to 50 m^3 and 0.11 to 135 ton based on block sizes and average measured density (Table 1). Field investigation indicated that weathering was developed on the left side of the study area, and unstable blocks in most parts of this section lay on residual soil or highly to completely weathered rocks (Fig. 5). As shown in Fig. 3a, blocks in zone 1 of the left side are located on an old spoon landslide with 3 m in depth. The occurrence of the landslide is a sign of relatively deep weathering. A joint study has been carried out where systematic joints are presented. Due to weathering action and the talus form of most zones, the join study was done on zones 2 and 3 on the right side and around the waterfall in zone 2 on the left side.

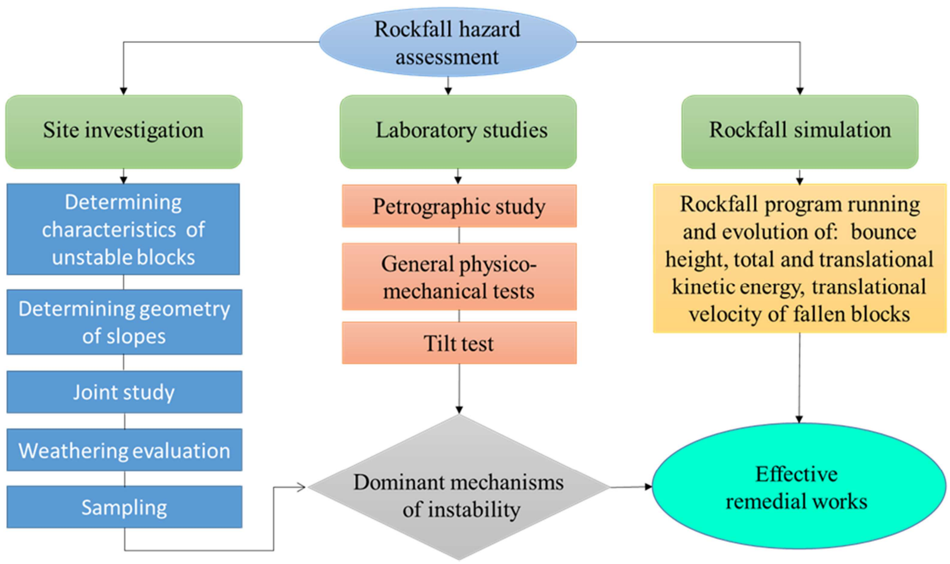

Fig. 4: Flow chart of this research process.

Table 1: Summary of site investigation results for the study area

Location	Right side						Left side	
Zone	1	2	3	4	5	Upper road	1	2
Overall slope	38	40	32	30	30	40		
Number of unstable blocks	30	28	61	18	31	25	39	41
Number of key blocks	4	16	13	4	5	25	18	35
volume-weight Max(m^3-ton)	4.69-12.67	12-32.5	12.5-33.8	14-37.9	50-135	26.2-71.1	7.5-20.2	48-129
volume-weight Min(m^3- ton)	0.06-0.16	0.04-0.11	0.06-0.16	0.2-0.54	0.25-0.67	0.12-0.34	0.07-0.2	0.19-0.5
volume-weight Ave(m^3- ton)	0.71-1.92	2.2-5.96	2.19-5.95	2.9-8.1	3.8-10	4.3-11.6	1-2.7	4.9-13.4

Fig. 5: Lying of instable blocks on completely weathered granite as basement.

Laboratory studies

In this study, a series of index rock mechanics tests and petrographic analysis has been done in the laboratory on chosen samples during the field investigation phase from the area. The results of petrographic studies on the porphiroid granite show coarse-grained and granular texture. The mineralogical composition of the rock includes 25% euhedral plagioclase, 24% subhedral orthoclase, 25% anhedral quartz, 23 % biotite, and 3% minor minerals such as muscovite and garnet. Based on this mineral composition, the porphyroid granite is known as monzogranite. As went earlier, the left side outcrop, which is covered by unstable blocks, shows weathering. Resistant minerals in the rock can chemically alter to softer, less resistant minerals during weathering. The occurred chemical and physical weathering leads to sericitization of considerable parts of biotite and feldspars and microfractures development in the rocks. The feldspars break down by hydrolysis and hydration into clays and colloids, which may migrate from the rock. Decomposition of some minerals to clay minerals and development of microfracture lead to rock be weak, and especially during rainfall and wetting some properties such as strength and durability dramatically reduce.

The results of physical and mechanical tests are summarized in Table 2. The tests were performed on both sound and weathered samples. The results show average porosity ranging from 1.04% in sound samples to 13.21% in weathered samples. Weathering lead to increases in quick water observation index from 0.312 to 6.46 in the rocks. Saturated density changes from 2.71 in sound to 2.16 (gr/cm^3) weathered samples, respectively. For assessment of deferential weathering effect on slope instability, a slake durability test was used. The obtained results indicated that the second slake durability test has been reduced from 99.76 % in sound rocks to 65.14% in weathered samples. Considerable reduction in durability indicated that deferential weathering can play important roles in rockfall occurrences, where sound blocks lie on weathered rocks. Mechanical properties are important factors in the evaluation of the degradation potential of the blocks during their movement toward the slope toe. Uniaxial compressive strength of the rock decreased while weathering occurred. The measured UCS values are128 and 12 MPa for sound and weathered rocks, respectively. Tensile strength was measured just for sound samples and obtained about 9.9 MPa. Based on the performed tilt test on the sound block state, the mean basic friction angle was calculated to about 34 degrees. This vital parameter was measured around 25 degrees when the sound sample was used on the weathered sample. As is clear, weathering decreases the basic friction angle and can eventually change a once-stable block into an unstable position and finally pull it down by gravity. Assessment of instability mechanism in the area proposed two different dominated mechanisms for the left side and right side. The slope aspect is the most critical factor which controls the type of instability. Based on the slope aspect, it is evident that right-side facing slopes experience far more freeze and thaw cycles than the left side facing slopes.

Table 2 .Physico-mechanical properties of Alvand monzogranitic rocks

Rock type	Parameters	Porosity(%)	QAI	γ_{sat} (gr/cm^3)	Id_2 (%)	UCS (MPa)	σ_t (MPa)	Φ_b (degree)
	Maximum	1.08	0.318	2.71	-	137	10.40	37
Sound rock	Average	1.04	0.312	2.71	99.76	128	9.9	34
	Minimum	0.99	0.304	2.70	-	119	9.2	32
	Maximum	15.14	6.78	2.23	-	14	-	26
Weathered rock	Average	13.21	6.46	2.16	65.14	12	-	25
	Minimum	12.17	6.24	2.08	-	8	-	21

The left side slope is in the shade most of the day, so that it will experience the least temperature variation during a day. So, snow will be thawed slowly, and the rocks on this side are in contact with water for a considerable time. Consequent to this condition is the development of weathering. As described, the main factors which play an important role in the left side instability are the high angle of slope and the development of a weathered basement. During rain, the shear strength of the weathered basement dramatically decreased and covered blocks will be detached from original lactation and moved toward the lower part of the slope. Inspection of right side zones indicated several sliding surfaces with the slope angle lower than the basic friction angle (Fig. 6). This means that the blocks will not be unstable just by the shear component of the weight vector, and external forces are needed as well. The external forces are associated with ice-jacking phenomena. Right side slopes will attract more sunshine and are subjected to high temperature variations over 24 hours. During a day, sunshine leads to the thawing of snow and the water will flow in cracks and joints. In the evening and night, the temperature will drop to below zero and the water will be frozen. The generated ice can produce two pressures.

Fig. 6: A view of key block KR43 detaching due to Ice jacking action

As is shown in Fig. 7, the pressures are perpendicular to the cracks and one of them, which acts on the sliding surface, leads to a decreasing basic friction angle. The other one applies additional shear forces, and both of them are playing instability roles. Also, repetition of the freezing-thawing cycles will make weak the rock strength and reduce basic friction angle due to fatigue action.

Fig. 7: A view of blocks detaching due to ice jacking action

Rockfall Analysis

In the surrounding slopes of the Ganjnameh valley, which consist of several unstable blocks, the predominant slope instability potential is rockfall, as has already occurred during 2005, which has led to the interruption of the site. In this research, rockfall simulation was carried out in all the zones using the RocFall V.4.0 computer software (Rocscience 2002) to evaluate characteristics of the probable rockfalls. Because of the high concentration of visitors in the valley, this simulation and risk assessment has particular importance. The program will determine some key factors of falling blocks such as velocity, energy, bounce height for the entire slope, and location of rock endpoints. Rockfall can also help in choosing remedial methods (RocFall user's guide, 2002).

Rockfall modeling requires some sufficient data, which can be obtained during field investigation. The most important parameters are the geometry of the slope, falling block's locations, sizes and weights, and especially slope surface characteristics. The Rockfall software proposed different surface definitions controlling horizontal and vertical coefficients of normal (Rn) and tangential (Rt) restitutions. These parameters control energy absorption at the contact points of the falling block with the earth's surface. Normal restitution is related to the elastic properties of the surface material, which depends on the type of material covering the surface and the presence of vegetation. In contrast, tangential restitution is depended on vegetation cover, surface roughness, and the radius of the falling rock itself (Dorren et al. 2004). Bedrock outcrops, asphalt, clean hard bedrock, soil with vegetation, talus cover, and talus with vegetation were considered as covering materials in the software, and restitutions parameters were proposed for each type. In this study, based on the literature review and each zone conditions and likeness to the proposed definitions, recommended normal and tangential restitutions were selected. The final Rn and Rt values used in this study are in the range of 0.32–0.35 and 0.8–0.55, respectively.The main envelopes, including the total kinetic energy, translational velocity, and bounce height envelopes, were extracted from the software and the other envelopes (translational kinetic energy, rotational kinematic energy, rotational velocity) were neglected. Based on the envelopes suitable location of the barrier was selected and some information such as total kinematic energy and translational and rotational velocities on the barrier was determined.

In the study area, 5 profiles (3 profiles on the right side and 2 profiles on the left side) were considered as rockfall trajectories. After rockfall simulations, some important parameters such as rock endpoints, kinetic energy, bounce height, velocity, and graphs of the envelopes were extracted for each profile.

The obtained bounce height envelope from profile 1 located between zones 1 and 2, indicated that most of the blocks are moved in rolling on the surface and might bounce up to 2 m just after crossing the track road of Alvand mountain climbing (Fig. 8). The total kinetic energy envelope shows that this parameter is gradually increased during falling and at the near toe of the slope is reached around 1800 kJ. Assessing translational velocity changes shows that in two locations, reach to maximum value around 18 m/s. The falling blocks hazard will threaten the safety of visitors in the Ganjnameh valley and threaten the safety of Alvand Mountain hikers. Based on the three crucial parameters envelopes, 185 m from the cliff is a suitable point for performing barrier. It should be noted that the barriers must be placed in the most appropriate areas. The best location is there which has minimum bounce height and kinetic energy and also will support most of the falling blocks. Analysis of total kinematic energy on barrier shows that about 71% of the energy of the blocks is less than 150 kJ, 93% have less than 1000 kJ, one block has an energy of about 3100kJ, and another block has 6000 kJ kinematic energy. The translational velocity of blocks on the barrier was determined and the results indicate that just 4 blocks have a velocity less than 5.5 m/s, and the remains have a velocity in the range of 8-13 m/s.

A summary of the rockfall analysis results of profile 2 located in zone 3 is shown in Fig. 9. This simulation illustrates that the falling blocks were moving in a rolling state and just in 5 locations show a little bouncing less than 1 m. Total kinetic energy variation more or less shows gradually increasing up to 155 m of the route and after that dramatically decreased. A close inspection of translational velocity changes in this zone indicates that this parameter more or less is varied similar to total kinetic energy.

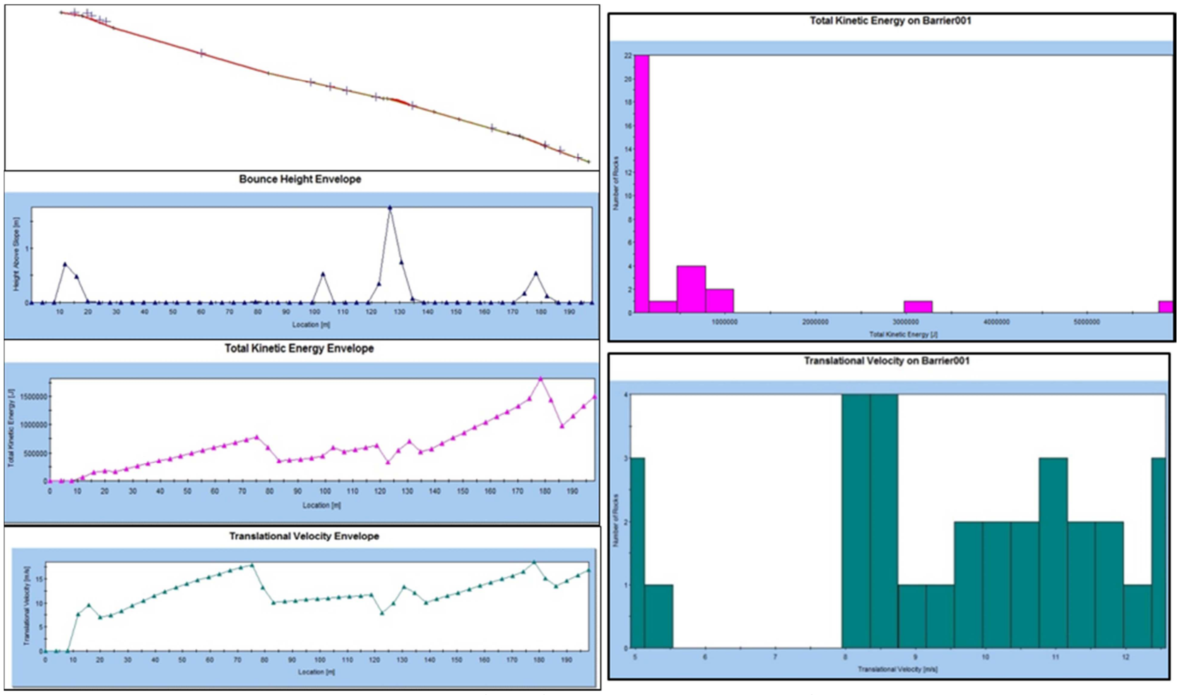

Fig. 8: Summary of rockfall analysis results on profile 1

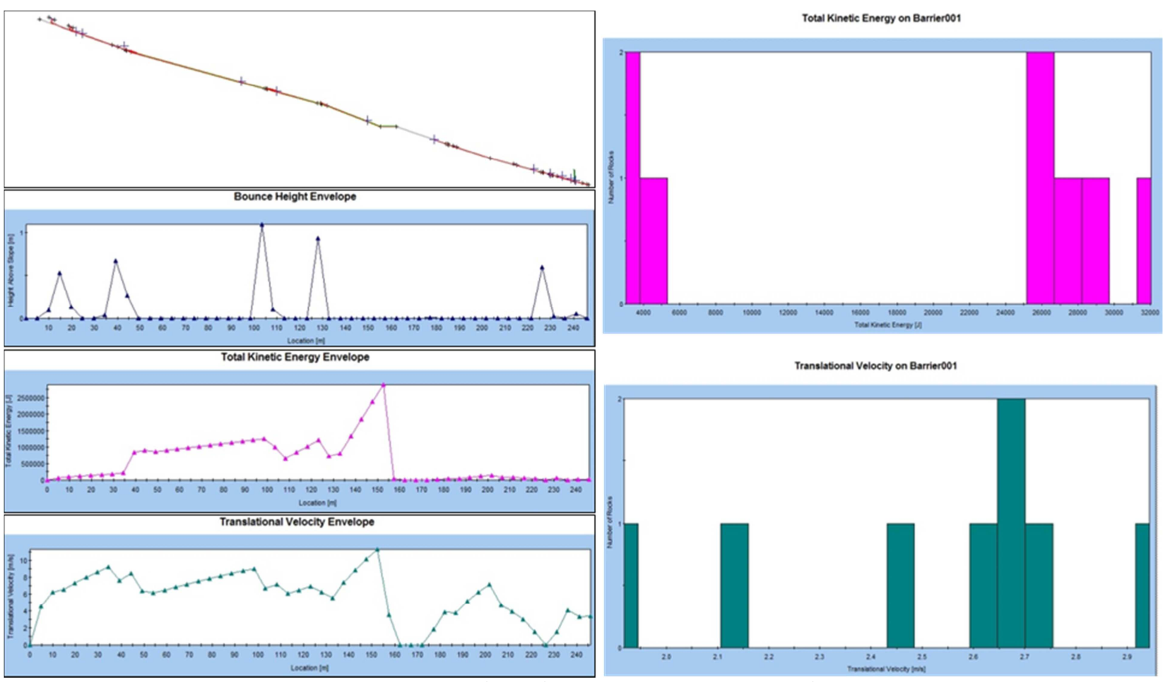

Fig. 9: Summary of rockfall analysis results on profile 2

The velocity changes from 0-11 m/s, and a considerable decrease around 155 m of the route is highlighted. After crossing 220 m of the route, energy and velocity are sensibly decreased. On the other hand, the area is near the toe of the slope. So, the barrier location was considered at 228 m. assessment of falling blocks impact on the barrier indicates that just 8 blocks will reach the barrier.

The total kinetic energy of three blocks is less than 5 kJ, and the rest blocks energy is about 26-32 kJ. The translational velocity of the blocks at the barrier location varied between 1.9-3 m/s with a dominated velocity of about 2.6 m/s.

Profile 3, which is crossed between zones 4 and 5, was rockfall analyzed and the obtained results were shown in Fig. 10. The bounce height analysis results indicated that some blocks can jump more than 3 m at the end of this slope because of the presence of a ditch and its berm. Nevertheless, in most parts of the route, rolling is dominated type of movement. The total kinetic energy envelope shows that this parameter after crossing about 60 m of the route, is steeply increased and finally reached up to 8000kJ. The kinetic energy of fallen blocks dependent on their masses. Translational velocity variation indicated that this parameter was gradually increased and in some locations was reached up to 12 m/s. based on the three envelopes, the best point for the installation of the barrier was determined around 135 m of the route. The impacts of falling blocks on barrier indicate that 14 blocks ac arrive at the barrier which 50 percent of them have total kinetic energy less than 250 kJ and most of the remains have values between 800 to 1900 kJ and two blocks have high energy around 4000 and 8000 kJ. Also, the translational velocity of the arrived blocks indicated that the average value of the velocity in this zone is around 7m/s. Moreover, a block with a velocity of more than 12 m/s was considered.

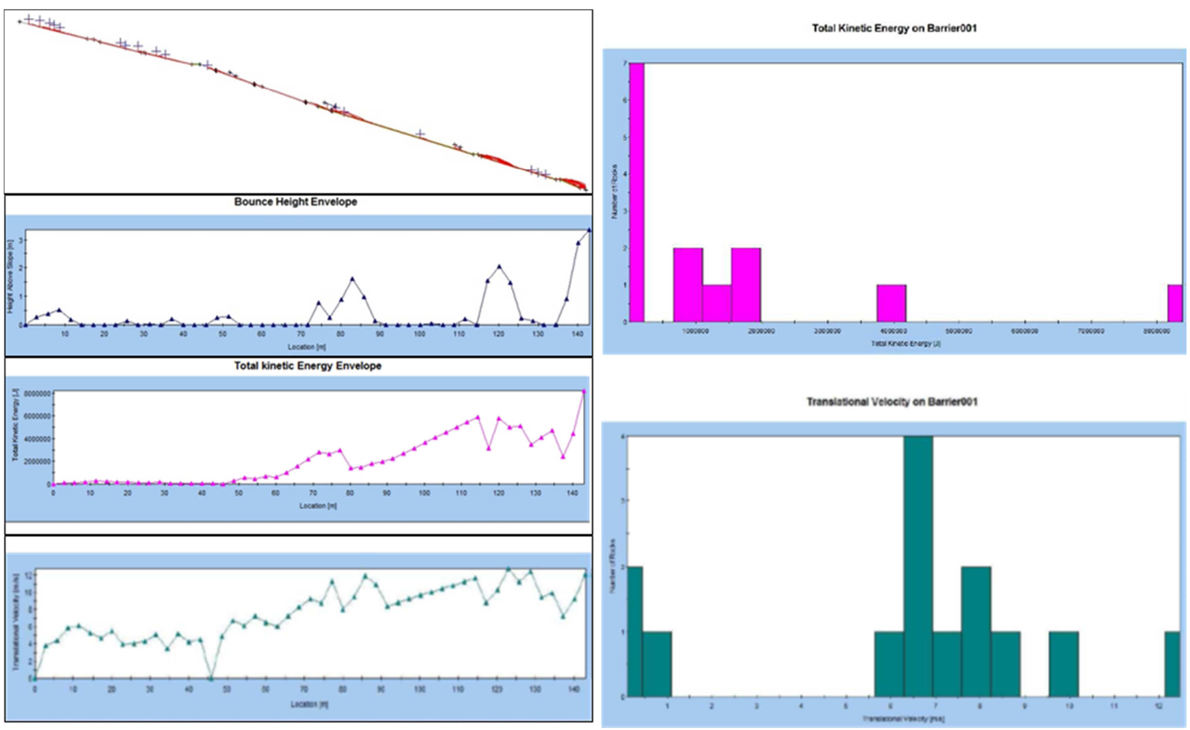

Fig. 10: Summary of rockfall analysis results on profile 3.

Profile 4 in zone 1 of the left side was simulated by rockfall software and obtained results were summarized in Fig. 11. The results show that falling blocks are moved in rolling and at some points have jumped up to 1.5 m. total kinetic energy envelope indicated this parameter regularly increased up to 22 m. After that, the trend of variation is irregular up to 122 m, which is the starting point of regular decreases of the energy. This energy maximum reaches 450 kJ and the dominant value of it is around 200-300 kJ. The translational velocity variation pattern is more or less similar to total kinetic energy with a maximum of 10 m/s velocity. Both total kinetic and velocity of this zone are considerable and on the other hand, the toe of this zone is the concentration location of Ganjnameh Inscriptions visitors. So, the risk of the area is high and should be decreased by a barrier. Based on the results, the area between 125-130 m of the route is the best location for the installing a barrier. Analysis of arrived blocks impact on barrier shows that 20 blocks will arrive at the barrier which 70 percent of them have total kinetic energy less than 25 kJ. The maximum total kinetic energy of the falling blocks on the barrier was measured about 80 kJ. The translational velocity of the falling blocks varies between 0-7 m/s with a dominant value around 4 m/s.

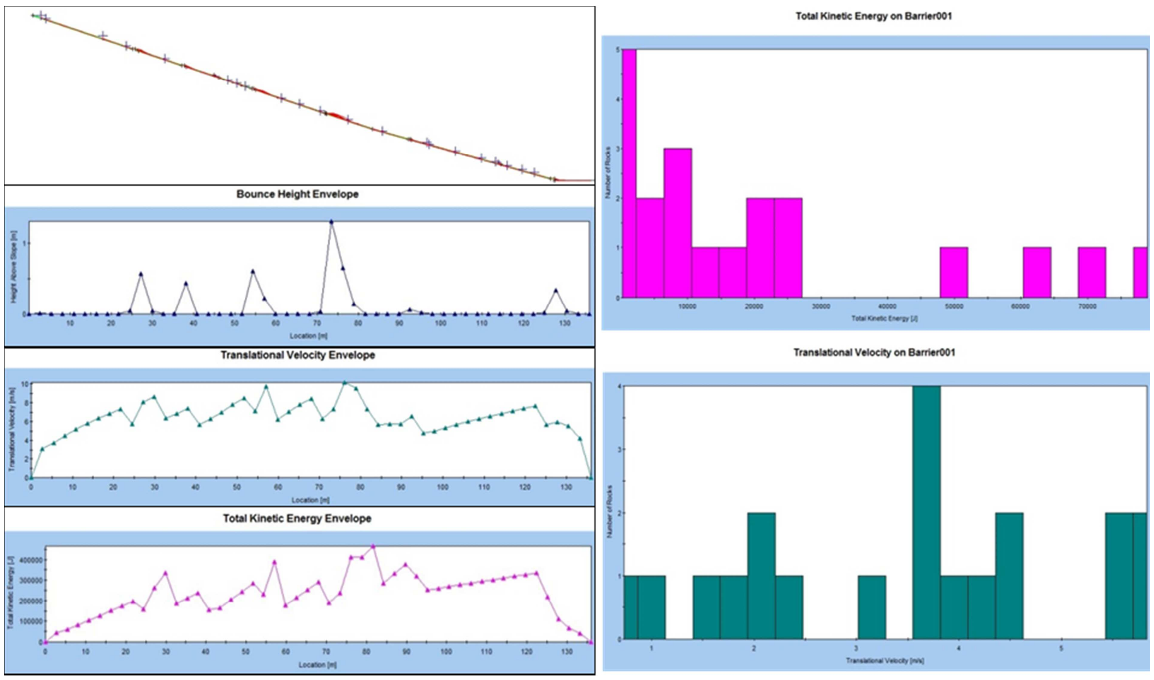

Fig. 11: Summary of rockfall analysis results on profile 4.

Profile 5 in zone 2 of the left side will be considered the most critical profile because of its high slope angle and presence of many key blocks. The results of this profile rockfall analysis were shown in Fig. 12. Rockfall simulation of this profile indicates that falling blocks are moved in rolling up to the ditch and its berm. The results also showed that some of the falling blocks might bounce up to 8 m heights after crossing this place. So, the hit point of the falling blocks passed the river and is located on track pavement and will threaten the safety of tourists and visitors of Ganjnameh waterfall. Variation of the total kinetic energy of the falling blocks was also measured. It was found that this parameter is beginning to increases from the middle part of the profile and maximum reached to 6000 kJ, which is very high intensity and can cause considerable damage to the risk elements such as human life. Translational velocity analysis illustrates that this parameter has an increasing trend up to 27 m of the profile and after that behave irregular and maximum will reach 18 m/s. Because of the high velocity of falling blocks, it is nearly impossible for people to dodge from falling blocks toward them. The location 55 m of the profile will be considered as the best location for performing a barrier. The barrier will be affected by the falling block. Still, the results indicate that more than 93 percent of the blocks have total kinetic energy less than 800 kJ, and just one block with an energy of about 4800 kJ has a high influence on the barrier, which will be removed before the barrier performing. The dominated translational velocity of the falling block in the barrier location is more than 12 m/s, which is relatively high.

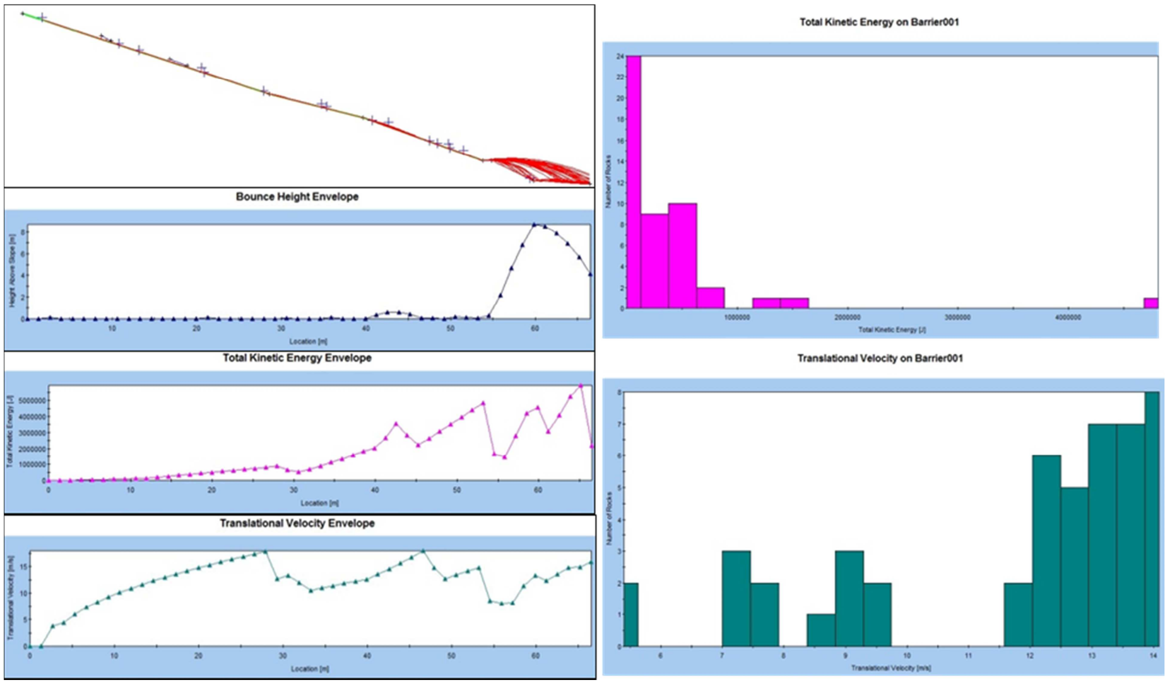

Fig. 12: Summary of rockfall analysis results on profile 5

Rockfall simulation indicates that all of the zones blocks will threaten tourists and visitors. It was considered that all of the falling blocks have convergence to the pavement between the Ganjnameh inscriptions and waterfall with a length value of about 100 m. consequently, visitors within this corridor would be dangerously subjected to rockfalls damage at any time. Hence, to avoid occurring a disaster, remedial measures and plans against rockfall hazard should be performed as soon as possible. The application of preventive methods in a cultural heritage area has some limitations. The used remedial methods must have minimum changes in the natural view. So, remedial methods with a nature-friendly appearance of the slopes should be chosen. The best methods for support of the slopes are depended on the instability mechanism and their engineering geological conditions. In all zones, cleaning the loose blocks is found as the best effective method. On the right side of the study area, all of the unstable blocks in zone 1, 80% in zone 2, 23 % in zone 3, 35 % in zone 4, 50% in zone 5, and around 5 % of instable blocks of upward of Alvand climbing track road should be removed. After cleaning the loose blocks, the rest would be supported using rock bolts and anchoring, grouting of joints and barriers. Both wire nets barrier and especially rocky (talus) barrier will be used at the optimum locations founded in rockfall 2D analysis. Remedial analysis of the left side indicated that 50 % and 23 % of falling blocks should be removed from zone 1 and 2, respectively. Because of the inscriptions in the boundary of zone 1 and 2, it should be noted that cleaning of these blocks must be done in a controlled and safe method. Drainage, terracing, tree planting, and deep-rooted vegetation are suggested as performable remedial methods because of the weathered basement of these two zones.

Conclusions

As reported in the past and presence of natural signs of historical rockfall events, Ganjnameh touristic area, located in the toe of Alvand Mountain, are subjected to severe rockfall hazard which needs proper attention and protection. The objective of this study was to investigate the rockfall problems of the Ganjnameh touristic area through a combination of site investigations, laboratory studies, and 2-

dimensional rockfall numerical modeling. Based on this research, the following results and conclusions can be drawn:

* Based on the site investigation and engineering geological assessment, it was found that the granitic rocks have at least three major joint sets in the form of an unloading joint set (relaxation joint) and two sets of tectonic joints. Based on the nature and spacing of the joints, the potentially unstable block size was determined.

* The slope gradient and slope aspect and related weathering actions are considered as the main controlling factors of rockfall in the area. The rockfall problems on the right side could be related to freezing-thawing activity and ice-jacking phenomena. In contrast on the left side, steep slope, presence of the weathered basement, and saturation by rain or snow are the main controlling factors.

* Laboratory works determined that the granitic rocks with 2.71 saturation density have good durability and strength properties, which are seriously affected by weathering and show a dramatic reduction, especially when the rocks are saturated.

* Five profiles were taken into consideration to simulated rockfall surrounding the valley. It was founded that the blocks of all profiles could reach the footpath between the Ganjnameh inscriptions and waterfall with dense tourists and visitors' activity. The maximum bounce height, kinetic energy, and translational velocity at the end of profiles (the boundary of the footpath) were measured about 8 m, 8000kJ, and 16 m/s, respectively. The falling blocks can have serious consequences when hitting the visitor. Profile 5 in zone 2 of the left side was the most dangerous zone because of its high gradient slope and maximum numbers of key blocks.

* To minimize rockfall hazards and risk, remedial works were recommended based on instability mechanism and also the nature-friendly point of view. These remedial works are including cleaning of loose blocks, rock bolts, joint grouting, drainage, vegetation, and flexible barriers.

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مقاله (علمی پژوهشی)

آنالیز خطر سقوط سنگ در منطقه توریستی گنجنامه، غرب ایران

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۱*. استادیار زمین شناسی مهندسی دانشکده علوم زمین دانشگاه صنعتی شاهرود
۲. دانشیار زمین شناسی مهندسی گروه زمین شناسی دانشگاه بوعلی سینا

چکیده

منطقه گنج نامه به عنوان یکی از جاذبه های تاریخی-فرهنگی و توریستی در غرب ایران بوده که به شدت به خاطر مشکل سقوط سنگ مورد تهدید قرار دارد. جاذبه‌های این منطقه باعث جذب هزاران گردشگر در سال از سراسر دنیا می‌گردد. در گذشته چندین مورد سقوط سنگ در این منطقه روی داده است. رخداد سقوط سنگ می تواند امنیت جانی بازدیدکنندگان را حین بازدید و بررسی این منطقه به خطر بیاندازد. هدف اصلی این تحقیق آنالیز مقدماتی از پتانسیل سقوط سنگ در این محل تاریخی می‌باشد. به همین منظور یک مطالعه بر پایه سه مرحله کاوش صحرایی، انجام آزمون‌های آزمایشگاهی و شبیه سازی سقوط سنگ صورت گرفت. در مرحله کاوش صحرایی اندازه بلوکهای ناپایدار، هندسه شیب و شرایط هوازدگی اندازه گیری شده و درزه نگاری و نمونه گیری انجام شد. خصوصیات فیزیکی و مکانیکی گرانیتها در آزمایشگاه تعیین گردید. انرژی کنیتیک کلی، ارتفاع جهش، سرعت انتقالی بلوک‌های سقوط کننده به عنوان خروجی شبیه سازی سقوط سنگ تعیین گردیدند. بر پایه نتایج به دست آمده، مکانیسم های متفاوتی برای ناپایداری تکیه گاه چپ و راست این منطقه به دست آمد. مشکل سقوط سنگ در تکیه گاه راست بیشتر در ارتباط با درزه‌داری و فرایند یخ زدکی – آب شدگی بوده، در حالی که در تکیه‌گاه پر شیب سمت چپ فرایند هوازدگی و اشباع شدگی مهمترین فاکتورهای کنترل کننده می‌باشند. نتایج مشخص نمود که مسیر پیاده رو بین کتیبه‌های گنج نامه و آبشار که بیشترین تراکم بازدیدکنندگان را نیز دارا می‌باشد، تحت خطر جدی سقوط سنگ از هر دو تکیه گاه و بخصوص تکیه گاه چپ قرار دارد. در نهایت برای کاهش پتانسیل سقوط سنگ و ریسک آن، روشهای بهسازی پیشنهاد گردید.

واژگان کلیدی: گنج نامه، سقوط سنگ، کاوش صحرایی، هوازدگی.

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