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Rockfall Hazard Analysis of Ellora Cave, Aurangabad, Maharashtra, India

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Abstract: ***The Ellora caves are located in Deccan Trap lava flows of upper Cretaceous to lower Eocene age. The terrain preserved one of the most historical places near Aurangabad city of Maharashtra, India. The Kailashnath temple is one of the most attractive caves and anticipated damage due to rockfall activity. The rockfall problem around the temple could be related to weathering, jointing and human intervention or a combination. In this study, rockfall hazard at Kailashnath temple is evaluated by 2D rockfall analysis. Different sizes of blocks are taken into consideration in the analysis based on visual observation at the site. The impact of fallen blocks on the Mandapa (Nandi Mandapa) structure is evaluated. The kinetic energy and velocity of the impacted blocks and damage caused by this impact on Nandi Mandapa has been evaluated. The obtained data are used to define the possible damage to Nandi Mandapa and based on the evaluation of the data; protection measures such as net fences are suggested with suitable height considering different sizes of the rock blocks. The height of the net fences has been figured out using equations proposed by Peila and Ronco (2009) and it is found as 1.49 m.***

Keywords: Ellora cave, Deccan Trap, Kailashnath, Rockfall, Mandapa, Net fences

1. Introduction

1.1 Presentation of the study site

Ellora cave is an archaeological site, situated 29 km North-Northwest of the city of Aurangabad at Aurangabad-Chalisgaon road in the Indian state of Maharashtra (Figure 1). The caves were built by the Rashtrakuta dynasty. It represents the epitome of Indian rock-cut architecture and UNESCO inscribed it as World Heritage Site 0. There are in total of 34 caves (Figure 2) in which 1 to 12 belongs to Buddhist , 13 to 29 belongs to Hindu and remaining 30 to 34 belongs to Jain religions [2].

The Kailashnath temple is one of the 34 monasteries and temples that extends over more than 2 km and was excavated side by side in the wall of a high basalt cliff. Kailashnath temple (cave 16) is a remarkable example of Dravidian architecture due to its rock-cut architecture and re minds Mount Kailash, the abode of Lord Shiva [2]. It was carved out in a single rock such as a megalith, more attractive for tourists. The excavation of the Kailashnath temple started at the top of the original rock (mainly basalt) and went downward making it as a vertical excavation. The ground plan of the Kailashnath temple is approximately equal to the area of Parthenon in Athens and it is 1.5-times high. Initially, Kailashnath temple was covered with thick white colored plaster resembling the scared icy Kailash Mountain in Tibet. The temple forms a U-shaped courtyard and has four main parts as follow;

I. Body of the temple,
II. Entrance gateway,
III. An intermediate Nandi shrine and
IV. Group of five shrines surrounding the courtyard

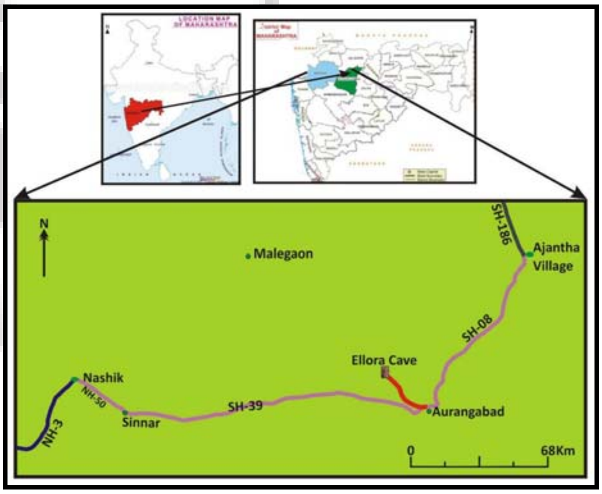

Figure 1 Location map of study area showing road networks

The entrance gate is also known as Gopuram and it serves as a screen between the scared temple and the outer world. After the Gopuram comes, a 7-meter high giant Nandi bull has been located in front of the main Shiva temple, which itself has been built on two storeys. Also, two Dhwajasthambhas, a free-standing pillar about 15-meter high were installed one on each side of the Nandi shrine. Next to Nandi bull, a largest structure inside the temple known as large Mandapa, hall of the temple and the main shrine of the Kailashnath temple collectively called as “NANDI MANDAPA”. The height of the Nandi Mandapa is about 29.3 m and it stands on 16 pillars.

This paper deals with the possible damage of the Nandi Mandapa situated within Kailashnath temple (cave-16) due to the probability of falling blocks from the top of the Kailashnath temple (Figure 3a) and its remedial measures. Rocfall 4.0 program has been used for the analysis and an extensive fieldwork has been conducted for identification of launching features of rockfall (Figure 3b).

Figure 2 Arrangement of the Ellora caves with increasing number from East to West. Study area is marked as rectangular blocks and shown in Figure 3a. (Source: http://en.wikipedia.org/wiki/Kailashnath_Temple,_Ellora)

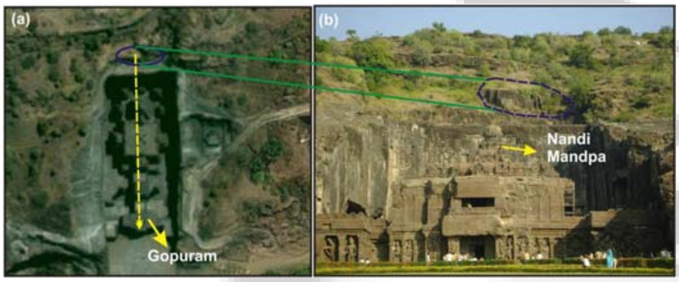

Figure 3 (a) Plan of the Kailashnath temple with profile marked as yellow dotted line used for rockfall analysis. (b) Shows possible location of rockfall blocks and also frontal portion of Nandi Mandapa. (Source: http://en.wikipedia.org/wiki/Kailashnath_Temple,_Ellora).

1.2 Geology of the Study Area

Ellora and its surroundings are located in a relatively flatter region of the mountain ranges well known as Western Ghats. The southern Indian plains suffer intense volcanic activities for many million years. The mineral rich rocky crust has been fetched out on to the surface due to these volcanic activities. However, in some other part of the flat plane, volcano erupted and formed abrupt hilly formations. One of the lava heads is located very close to the Ellora caves near to the cave 32 through which lava once flowed. Several flows have been identified in the study area by researchers [3]. These are marked by an alternating sequence of 'Aa' and 'Pahoehoe' in which 'Pahoehoe' flows are relatively more homogeneous in nature without any clear-cut divisions except for the glassy crust at the top of the flow [3]. It is characterized by alternate massive and vesicular units. Quartz veins with thickness varying from 0.5 cm to 2.0 cm were recorded in the field (Figure 4) and these quartz veins lie near the lineaments [4].

2. Literature Review

A rockfall analysis using Rocfall 4.0 around Afyon castle, Turkey has been carried out by Topal et al. [5], for the assessment of rockfall. The result of their works i.e. runout distance, maximum bounce height, kinetic energy and velocity of falling blocks have been used for exact preparation of the rockfall hazard zonation. Chris et al. [6] conducted rockfall simulations at Gibraltar for development of housing project and adopted same program [7] to identify risk region and proposed proper safety fences. The historical Kastamonu Castle in Turkey has been studied by Topal et al. [8] and they analyzed 17 profiles in different directions. The output rockfall parameters were used for rockfall hazard zones and the suitable rockfall protection measures have been proposed i.e. rock-bolting and protective fences.

Figure 4 Quartz vein in Basalt at the Kailashnath temple in Ellora cave

However, the study of rockfall in India is an emergent subject and till now few research documents are available on rockfall studies in different parts of the country. Ansari et al. [9] studied the stability of Ajanta caves, Maharashtra and identified that some locations are vulnerable to rockfall and needed urgent protection. Also using Rocfall program, they evaluated rockfall parameters and proposed barrier capacity and their exact location. Ansari et al. [10] identified the relation between mass of the falling blocks and bounce height, whereas, Ahmad et al. [11] discussed about the assessment of the rockfall for SH-72 using Rocfall and UDEC program. Also, similar study has been done for the stability of road cut cliff along SH-121, Maharashtra by Singh et al. [12]. A rockfall risk analysis has been done by Ansari et al. [13] near Nashik, Maharashtra, India.

2.1 Rockfall Analysis

Rockfall is the gravity driven motion of the rock blocks detached from the top of the cliff and/or steep slope and involves rebound, free flight, sliding and rolling [14]. There are number of causes to the rockfall but the most commonly is related to the rainfall. Once, the rock block detached from the cliff and/or steep slope it will fall, bounce, roll and slide along the slope and come to rest as the velocity diminishes ([15], [16], [17] and [18]). Several researchers have described in details rockfall assessment and they have suggested different remedial measures which are site specific ([15] and [18]).

The Rocfall 4.0 program works on the principle of lumped mass i.e. the mass of each rock block is concentrated at the center of gravity [7]. Due to this mechanism, it should also know that the different size and shapes effects must be accounted for an approximation of or adjustments to other properties. The rockfall studies always include the motion on the vertical and horizontal direction. . The block follows ballistic trajectory motion given by equations 1-6 and the air resistance is usually neglected [19].

Vertical motion	$S_y=V_{yo}t-0.5gt^2$ ....(1)	*Horizontal motion*	$S_x=V_{xo}t$ ...(4)
	$V_y=V_{yo}-gt$.........(2)		$V_x=V_{xo}$...(5)
	$A_y=-g$.........(3)		$A_x=0$......(6)

Where;
S_x = horizontal distance travelled (m)
S_y = vertical distance travelled (m)

V_{xo} = initial horizontal velocity (ms^{-1})
V_{yo} = initial vertical velocity (ms^{-1})
V_x= horizontal velocity after impact (ms^{-1})
V_y= vertical velocity after impact (ms^{-1})
t = time interval (s)
A_y=vertical acceleration (ms^{-2})
A_x=horizontal acceleration (ms^{-2})

Simulation of rockfall always depends on the estimation of the crucial parameters. In this study, all of these parameters are obtained during the field visit; however, the coefficient of restitution is taken from the literature ([9]; [10]; [11] and [13]). The study site is not suitable for in-situ testing for coefficient of restitution due to archeologically susceptive and protected area. Moreover, if some in-situ testing is conducted, the falling blocks from the top of the Kailashnath temple can cause serious damage to the historical structure and also be a risk to the life of the tourists visiting the cave each day. Density of the rock blocks has been determined in laboratory as per standard [20].

The slope geometry and surface roughness also play equally important role during rockfall study. The roughness of surface always controls the shear behavior of rockmass as well as movement. To get the exact nature of the slope profile and surface roughness a survey was performed and also a profile of rockfall analysis has been acquired (Figure 5). The slope angle affects the runout distance as described by Mearz et al. of the falling blocks [21]. If the slope face have un-weathered rock, free from vegetation then it will provide no retardation to the falling blocks as compared to the surface covered with vegetation or talus material [22]. This retardation capacity of the slope material is mathematically expressed as normal coefficient of restitution (Rn) and tangential coefficient of restitution (R_t). The normal coefficient of restitution (Rn) that work perpendicular to the slope and is affected by the properties of the material covered the surface of the slope. However, the tangential coefficient of restitution (R_t), acts parallelly to the slope and depends on the slope surface roughness. The two restitution coefficients are assumed as overall values which take into account all the impact considerations, including the deformation work, the contact sliding and the transfer from rotational to translational moment and vice versa. . The coefficient of restitution has been calculated by in-situ test, by empirical data or by laboratory experiments ([18]; [23]). However for the present study coefficient of restitution has been taken from the recent study on Deccan Trap Basalt ([10];[11]). This is because of the reason that in-situ tests were dangerous to perform at the cave site as mentioned earlier. Therefore, the values of normal and tangential coefficient of restitution used for the analysis are 0.35 and 0.85 respectively. Also parameters used for the rockfall analyses are mentioned in Table-1.

Table 1 Parameters used in rockfall analysis

Parameters	*Values*
Number of Rockfall	100
Coefficient of normal restitution	0.35 ± 0.05
Coefficient of tangential restitution	0.85 ± 0.05
Friction Angle (°)	30
Slope roughness	2
Initial velocity (m/s)	1±0.5
Density of the rock block	2600kg/m^3

2.2 Analysis for Preventive Measures

To prevent the rock block fall on the cave temple, several preventive measures are identified, however, due to aesthetical and archaeological problem, net fences has been chosen as the best solution to catch the falling blocks. The design of the net fences should be according to equations proposed by Peila and Ronco [28]. The design height (H_D) can be calculated using the formula proposed by Peila and Ronco [28] and mentioned below;

$$H_D = H_{95} * \gamma_{TR} * \gamma_{DP} + f \quad \text{.........} (7)$$

Where;

H_{95} = height of the boulder trajectory over the slope and is taken at the 95% of the calculated trajectories.

γ_{TR} = factor of safety on quality of the simulation analysis and has the following values

(i) 1.02 for 2D and 3D simulation calibrated by back analysis
(ii) 1.07 for 2D simulation on the basis of literature (bibliographic) values

γ_{DP} = factor of safety for the quality of topographic model and has the following values

(i) 1.05 for laser scanning model
(ii) 1.1 for normal topographic model
(iii) 1.15 no model (cross section derived from large scale map)

f = half of the average size of the boulder or falling blocks (generally average radius of the fallen blocks).

3. Results and Discussion

3.1 Rockfall Analysis

The rockfall analysis has been performed at the back of the Kailashnath temple and slope geometry are given in Figure 5. The impact of the falling blocks on the Nandi Mandapa has been calculated using Mandapa as a barrier location in the path of the rockfall. The typical rockfall trajectory is shown in Figure 6. The kinetic energy and velocity of the impacted rock blocks on the Mandapa and its impacted locations were determined by rockfall analyses (Figure 7). The impacted maximum total kinetic energy found as 64.4 kJ for 2000 kg blocks and the value for maximum velocity is equal to 10.9 ms^{-1} for 1500 kg blocks. It was also observed that the impacted energy increases rapidly from 18.7 kJ for 500 kg to 56.5 kJ for 1000 kg. However, 1500 kg to 2000 kg does not involve a sharp increase. Moreover, it has been observed that most of the rock blocks hit the Mandapa but direct impact has not been observed. The results of the rockfall analysis using different size of rock blocks are mentioned in Table-2.

3.2 Rockfall Protection Measurements

The schematic diagram for the net fences is shown in figure 7a and the data for the analysis is mentioned in Table-3. Also location of the net fences is shown in figure 7b and using the method proposed by Peila and Ronco [28], height of the net fences has been identified and mentioned in Table-3. The value of height of the net fences is found to be 1.49 m to protect the miss-happening at the site.

Table 2 Analysis results of the rockfall using different rock blocks size

Size (Kg)	*Max. Impact Energy (kJ)*	*Max. Impact Velocity (m/s)*	*Max. Height of Impact (m)*
500	18.70	8.54	5.70
1000	56.51	10.56	6.96
1500	64.00	10.93	5.94
2000	64.36	10.00	5.04

Table 3 Calculation of the design height for net fence as per equation proposed by Peila and Ronco (2009).

Parameters	*Values*
H_{95}	1.05 (m)
γ_{TR}	1.07
γ_{DP}	1.05
f	0.31 (m)
H_D	1.49 (m)

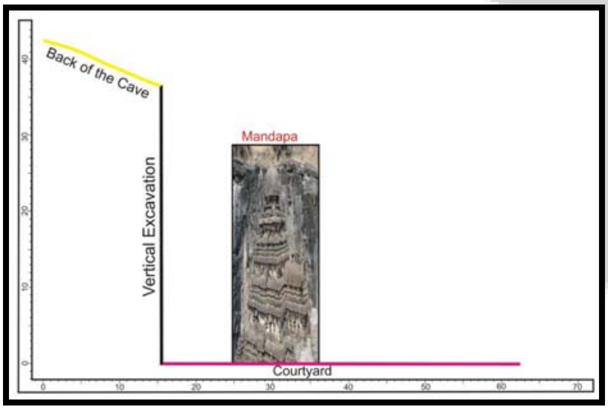

Figure 5: Typical profile for the rockfall analysis. Also showing position of Nandi Mandapa.

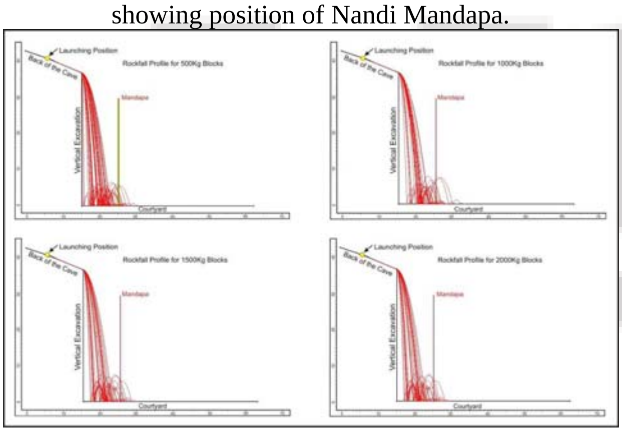

Figure 6: Rockfall trajectories for different sizes of the falling blocks.

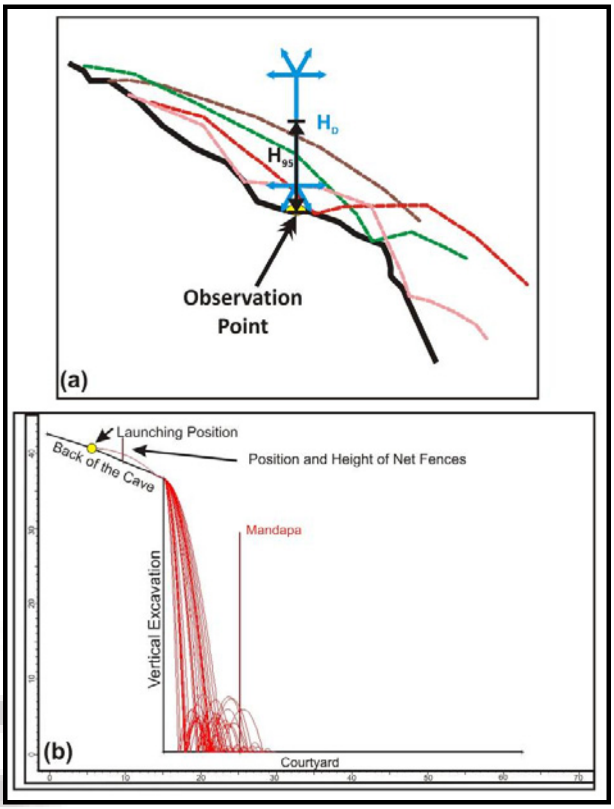

Figure 7: (a) Schematic diagram for the design height of net fences (b) location and height of proposed net fences at Kailashnath temple.

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4. Conclusions

The conclusions achieved from the current study can be drawn as follows;

1) An extensive field study has been performed to identify the rockfall hazard at the Kailashnath Temple (Nandi Mandapa) that includes determination of the potential detached blocks at the top of the temple.
2) Two-dimensional rockfall analyses have been performed with varying size of the falling blocks i.e. ranging from 500 kg to 2000 kg.
3) The results of the rockfall analyses revealed that fallen blocks will have high impact velocity and energy on the temple and will cause temple to the structure. The maximum impacted kinetic energy and velocity are found as 64.4 kJ and 10.9 m/s. These values indicate a highly dangerous situation for the Nandi Mandapa.
4) There are various rockfall hazard mitigation measures available but due to aesthetical problems only net fences is applicable for the protection of fallen rock blocks. The height of the net fences has been calculated using the equation proposed by Peila and Ronco (2009) and it is found to be 1.49 m.
5) This study will help to identify the problem of rockfall at the Kailashnath temple and its remedial measures.

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