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2D and 3D Rockfall Hazard Analysis and Protection Measures for Saptashrungi Gad Temple, Vani, Nashik, Maharashtra – A Case Study

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ABSTRACT

The Saptashrungi gad temple (SGT) situated on basaltic hills belongs to Deccan volcanic of Upper Cretaceous to Lower Eocene, is one among the 51 Shakti Peeths and most holy place for pilgrims. Rockfall is a major problem in the past and causing danger to the lives of the villagers settled at the toe of the SGT hill as well as the pilgrims who perform parikrama along the tracks. On the evening of 16 April 2011, an old woman died due to rockfall at SGT hill when she was performing parikrama, moreover, two persons got injured during the deliverance process of this old woman from the continuous rockfall activity. The problem of rockfall could be linked to rainfall, jointing, weathering, man-made or the compounding of all. In this research, the rockfall hazard analysis at SGT hill is assessed using both 2D and 3D rockfall programs along the two parikrama paths: Parikrama Path 1 (or the Badi Parikrama Path 'BPP'), and Parikrama Path 2 (or the Chhoti Parikrama Path 'CPP'). Also, the study area of the SGT hill has been divided into eight zones (Zone#01 to Zone#08), based on field observations, orientations of joint sets and hill slope faces and eighteen topographic profiles (AA' to RR') have been taken from these eight zones for rockfall analysis. A detailed topographic survey along with field investigation has been carried out along the temple for ascertaining the nature of rock, discontinuity orientations, and slope geometry. DEM has been generated using topographic profile in ArcGIS to facilitate the 3D rockfall analysis. Maximum rock block sizes are taken into the analysis and run-out distance, bounce height, kinetic energy and velocity of the basaltic blocks are evaluated separately. Based on the analyzed data, the rockfall hazard zone map has been prepared and site having potential rockfall risks have been identified. Finally, wire/net meshing has been proposed after removal of unstable blocks as a stabilization and protection measures.

It is worth mentioning here that for the first time rockfall hazard assessment was made in such detail for a site. Suggestions made are implemented by the State Government for the protection of the temple as well as the life of pilgrims performing the parikrama from the rockfall.

INTRODUCTION

Rockfall is fast motion of a boulder and/or boulders down a slope through free-fall, bouncing, sliding or rolling under the influence of gravity (Varnes, 1978). Rainfall, joints, weathering, tree-roots, earthquakes, anthropogenic activities or the combinations of all may cause rockfall. The results of the rockfall are socio-economical, i.e. loss of life, damage to the infrastructures and loss of the properties. Due to its socio-economic impacts, rockfall incident and its remedial measures should be considered for infrastructure planning in rockfall hazard zones. Geo-mechanical properties such as restitution coefficient, surface roughness, sliding and rolling resistance as well as structural features of the slope and falling rock-blocks affect the movement of blocks from free-fall to bouncing, rolling and/or sliding (Dorren, 2003; Ansari et al., 2012; Ahmad et al., 2013). Moreover, changes in slope profile may cause two or more rockfall modes (Ritchie, 1963; Ahmad et al., 2013; Ansari et al., 2016a).

Rockfall analysis can be performed by using empirical method, experimental method or computer modeling technique (Hoek, 1987; Evans and Hungr, 1988; Dorren, 2003). There are also many commercial 2D and 3D modelling programs available in the market such as CRSP (both 2D & 3D), Rockfall, rotomap, Rocfall, Rockfor3D, Rockfall Analyst and STONE (Pfeiffer et al., 1989; Hoek, 1987; Scioldo, 1991; Stevens, 1996;Guzzetti et al., 2002; Dorren, 2003; Lan et al., 2007). These programs are designed to predict the rockfall paths, i.e. rockfall trajectories, runout distance, velocity and kinetic energy as well as bounce height. Hazard zonation map for rockfall can be prepared after the rockfall analysis and based on these maps, proper remedial measures such as rock removal, netting, wire meshing, rock bolting and rockfall barrier can be proposed.

Chris *et* al. (2006) conducted rockfall simulations at Gibraltar for development of housing project and adopted same 2D program (Rocfall 4.0) to identify risk regions and proposed proper safety fences. Rockfall analysis using 2D program has been done around Afyon castle, Turkey by Topal et al. (2007), for the assessment of rockfall. The result of their work 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.

However, the study of rockfall in India is an evolving field and till date, only a few researchers have been working on the rockfall problems. Ansari et al. (2012) identified the relation between the mass of the falling blocks and bounce height. Ahmad et al. (2013) explained the assessment of rockfall based on increasing weight as well increasing heights. Similar study has been done for the stability of the road cut cliff along SH-121, Maharashtra by Singh et al. (2013), Rajesh et al. (2017) along highway sections NH-109 in Uttarakhand Himalaya and Sharma et al. (2017) along NH-222 at Malshej Ghat, Maharashtra. Ansari et al. (2014a&b) studied the stability of the Ajanta caves, Maharashtra and identified locations that are vulnerable to rockfall and proposed barrier as a remedial measures. Ansari et al. (2014c) near Nashik, Maharashtra, India, have performed a rockfall risk analysis. However, until date, no 3D rockfall analysis has been done for the rockfall hazard assessment in India.

In this paper, detailed rockfall hazard assessment for Saptashrungi Gad Temple (SGT) hill has been performed due to the vulnerability of the area to rockfall which could cause damage to the temple as well as risking the lives of villagers and pilgrims. The ritual involves performing the parikrama along both the parikrama paths, i.e. Parikrama Path 1 (or the Badi Parikrama Path 'BPP') located at the

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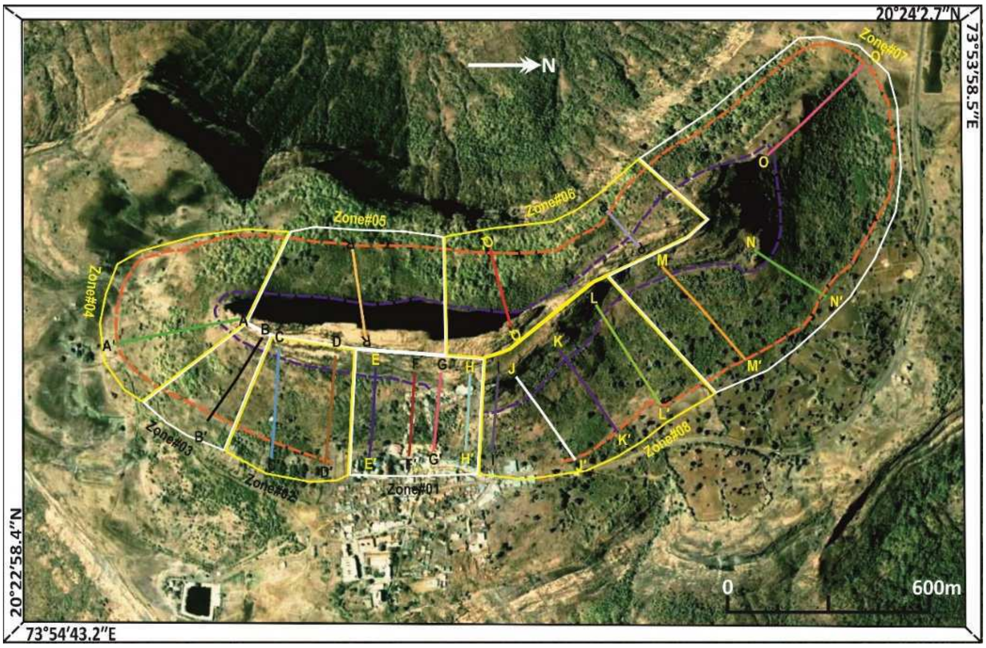

Fig.1. View of SGT hill showing parikrama paths. Blue and orange lines indicate CPP and BPP respectively. Also, showing zones (Zone#01 to #08) along with topographic profiles (AA' -RR'). (Source: map.google.com)

toe of the SGT hill, and Parikrama Path 2 (or the Chhoti Parikrama Path 'CPP') located 200m above the BPP (Fig. 1). The study area of the SGT hill has been divided into eight zones (Zone#01 to Zone#08) to perform 2D rockfall analysis, based on field observations, orientations of joint sets and hill slope faces. Eighteen topographic profiles (AA' to RR') have been taken from these eight zones for rockfall analysis (Fig. 1).

The stability of SGT hill has been evaluated by Ansari et al. (2016b). Though the analysis identify that majority of the slopes are stable in nature. However, it is found that rockfall is frequent phenomena at the SGT hill (identified based on fresh rock blocks found on the parikrama paths during field investigations). To assess the problem of rockfall at and near to the SGT, geotechnical survey was conducted and dimension of fallen rock blocks was measured. Coefficient of restitutions (COR) and friction angle has been calculated by laboratory experiments and surface roughness were estimated using inclinometer. Afterwards, rockfall analysis has been conducted along eighteen topographic profiles. The outcome of the analysis, i.e. rockfall runout distance, bounce height, velocity and kinetic energy have been used to prepare a rockfall hazard zonation map. The zonation map helps to predict the locations for the proper remedial measures such as rock removal, wire netting, wire meshing, rock bolting and rockfall barriers.

GEOMORPHOLOGY AND GEOLOGY OF THE AREA

The SGT is situated on the top of the hill range known as Saptashrungi, comprising of seven hills and locally called as Gad. SGT is a holy place for the pilgrims and large number of pilgrims visits the historic temple every year. The SGT is one among the 51 Shakti Peethas and widely known as three and half Shakti Peethas of Maharashtra. The study area is about 60km north of Nashik city, connected through State highway (SH)-17 and national highway (NH)-3. The NH-3 connects to SH-17 that reaches the SGT hill, located near the village Vani (Fig. 2). The annual rainfall is 98.1mm to 146.1mm in the month of June to September with maximum of 206.4mm in July.

The residual hill ranges and the intermediate valleys are well developed on a table land surface forming the main geomorphic element of landscape in the area. Approximately, 60 million years ago, the outpouring of basic lava through fissures formed horizontally bedded basalt over large regions. Variations in their composition and structure have resulted in massive, well-jointed steel-grey cliff faces alternating with structural benches of vesicular amygdaloid lava, all of which contribute to the pyramidal-shaped hills and crest level plateau or mesas. The temple is situated on a basaltic hill at a height of 1412m. The area exposes thick pile of basaltic flows with a number of basic and rare acid intrusive belonging to Deccan volcanic of Upper Cretaceous to Lower Eocene age of Sahyadri Group. The entire lava flow has been separated into three formations viz. Salher Formation, Lower Ratangarh Formation and Upper Ratangarh Formation in ascending order of the Sahyadri group. The lower most, Salher Formation, is conspicuously dominant in the lower reaches and mainly consists of compound flows. The overlying thick pile of largely compound flows is known as Lower Ratnagarh Formation and the next overlying group of compound flows exposed is called Upper Ratnagarh Formation. (Mahoney et al., 1982; Beane et al., 1986; Ansari et al., 2012).

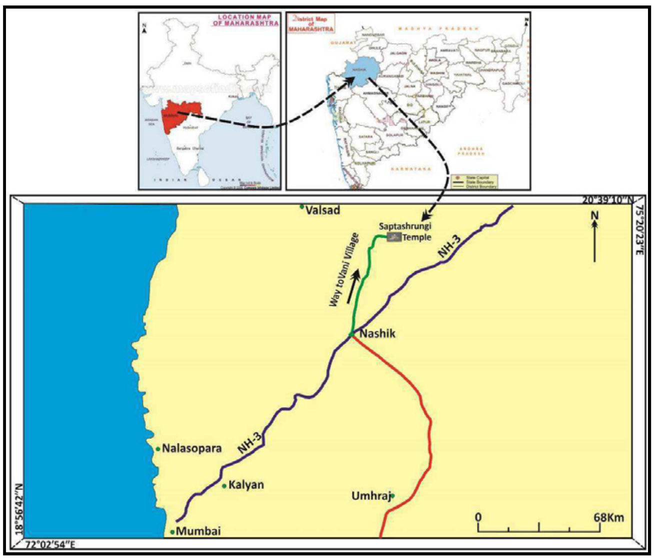

Fig.2. Location and accessibility map of Saptashrungi Gad Temple.

Due to frequent risk of rockfalls in the past, the village at the toe of the hill and the devotees are under treat. Many pilgrims have been injured during these rockfalls; some being fatal. (Maharashtra Times, 2011; Ansari et al., 2012, 2014c).

FIELD OBSERVATIONS AND ROCKFALL ANALYSIS

A detailed field study was performed to collect the geo-engineering characteristics of the site. Many rock blocks were identified at the toe of the hill as well as at the parikrama path indicating past rockfall. Scan line surveys was conducted for discontinuity measurements at different locations. Kinematic analysis divulged that wedge failure is the prominent type of failure at the temple area. The discontinuity surfaces are rough in nature and no water seepage was observed at the temple area. In addition, spacing of the discontinuity varies from cm to few m, causing small to large size blocks detachments, the largest fallen block observed both at the toe of the hill and parikrama path is about 20-30 tons in weight. Moreover the aperture of the discontinuities is also few cm to few mm.

Slope geometry and COR is an important parameter for rockfall analysis. A topographic survey on a scale of 1:1000 was done to collect the exact slope geometry. Contour map as well as the profile has been generated using these topographic surveys. Also, a DEM has been prepared in ArcMap to facilitate 3D rockfall analysis. The slope as well as the fallen rock blocks are mainly composed of basaltic rock. Normal and tangential coefficient of restitution for basalt was identified in a laboratory experiment. Spherical basaltic balls were dropped on a basalt slab clamped on a tilt-apparatus. Based on the experimental results it was found that the normal and tangential coefficient of restitution is 0.35 and 0.85 respectively (Ansari et al., 2014d). Tilt test helps to identify the value of friction angle and was found to be 30±2°. The slope surface roughness influences the contact angles between falling rock blocks. Also, it changes the mode of transport, i.e. sliding/rolling into bouncing. For the present study, slope surface roughness was carried out on the lower part of the slope with an inclinometer fixed on a straight edge of 100cm length. Upper part of the slope is inaccessible for inclinometer survey, so the surface roughness of this part was estimated from available survey data, as the upper slope face is very steep causing relatively low impact by fallen rock blocks, hence, the accuracy of surface roughness by survey data is enough for the upper part of the slope. Lastly, 1m/s value was chosen for the initial velocity as wind and rain could cause the rockfall and 1000 rock blocks were considered for the analysis. Table 1 shows all the parameters used in the rockfall analysis.

Table 1. Input parameters for Rockfall program

Parameters	Values
Number of Rockfalls	100.0
Normal Coefficient of Restitution (for slope 75°-85°)	0.35+0.05
Tangential Coefficient of Restitution (for slope 75°-85°)	0.85+0.05
Normal Coefficient of Restitution (for slope 55°-75°)	0.33+0.05
Tangential Coefficient of Restitution (for slope 55°-75°)	0.82+0.05
Weight of Falling rock mass (kg)	3000
Minimum velocity cutoff (m/s)	0.1
Friction Angle	30°
Slope Roughness	2.0°
Initial Velocity (m/s)	1+0.5

RESULTS AND DISCUSSION

2D Rockfall Analysis of SGT Hill

Rocfall (Rocscience, 2004) is 2D program available commercially, for finding probabilistic rockfall trajectory. The selection of 2D Rocfall program for SGT hill was based on the program's simplicity and speed of simulations. The program is based on lumped mass approach, i.e., rock block is considered as a simple point with rockmass concentrated at the center of gravity. Rock block is modelled in Rocfall as a particle with a specified mass, which is a random variable. The rockfall source areas on a slope are defined either as point seeders or as line seeders. A point seeder releases simulated rocks from a single point on the slope profile, whereas a line seeder allows the user to select a continuous area from which simulated rocks can originate. The last input parameter for rockfall analysis is the initial conditions of the rock blocks that includes the initial horizontal and vertical velocities along with the launching position of the rock blocks. Almost all parameters in Rocfall can be defined by either a constant or a random variable, which specify the mean value and standard deviation of parameters. The rockfall analyses have been performed in detail for each zone and discussed below:

Zone#01: The zone#01 comprises of four profiles EE', FF', GG' and HH'. The profile HH' is along the temple. The rockfall analyses are shown in Fig.3 (P1-P4). The output of rockfall analysis is runout distance, bounce height, kinetic energy and velocity. Almost all rock blocks have reached to BPP after either a direct impact or a partial impact with CPP. The maximum kinetic energy is encountered for profile HH', after a direct impact of rock blocks with the temple. The lowest kinetic energy is for profile GG'. This is the lowest value of kinetic energy encountered for any profiles at SGT hill and the possible reason could be the geometry of slope, i.e., gentle slope angle as compared to other slope geometries of the profiles. The result of the low kinetic energy cause the rock blocks to stop before reaching BPP. The high value of bounce height at zone#01 is recorded for FF' with a value of 37.14m; however, the lowest value is 5.79m for GG'. All simulation results are tabulated in Table 2.

Zone#02: Profiles CC' and DD' come in zone#02 with velocity >40m/s and kinetic energy >2700kJ for CC' and >3000kJ for DD'. The rock blocks partially hit the CPP for profile CC', whereas, it jumped over the CPP and reached to BPP for profile DD' as shown in Fig. 4 (P5-P6).

Zone#03, Zone#04 and Zone#05: Zone#03, zone#04 and zone#05 contain profiles BB', AA' and RR' respectively. Profiles BB' and RR' indicate the impact of rock blocks with CPP and finally reaching to BPP, however, for AA' the rock blocks stopped before BPP [Fig. 5(P7-P9)]. The maximum bounce height is shown by RR' and has a value of about 82.0m. The cause of the high value of bounce height could be explained by the slope geometry for profile RR' ; it is evident that upper part of the slope is almost vertical causing high value of bounce height. The kinetic energy is between 2000kJ to 3000kJ for profiles AA' and BB' respectively. However, the value of kinetic energy is >4800kJ for RR'.

Zone#06: The results of the rockfall analysis for profile PP' and QQ' is shown in Fig. 6(P10-P11). Both profiles show that the rock blocks reached to BPP after impacting CPP. The maximum values of kinetic energy are about 2200kJ and 1900kJ for profile QQ' and PP' respectively. Similarly, QQ' has the maximum velocity with a value of 36.88m/s but with lower bounce height as compared to PP'.

Zone#07: This zone comprises of profiles MM' , NN' and OO' and the results are shown in Fig.7 (P12-P14). Based on rockfall analysis, it has been observed that rock blocks reaching to BPP are only for profile NN' after impacting CPP. In addition, for profile MM' and OO', rock blocks stopped at the toe of the slope, i.e. at the zone of deposition. The high value of kinetic energy is achieved by each profiles after hitting the CPP with the lowest value for

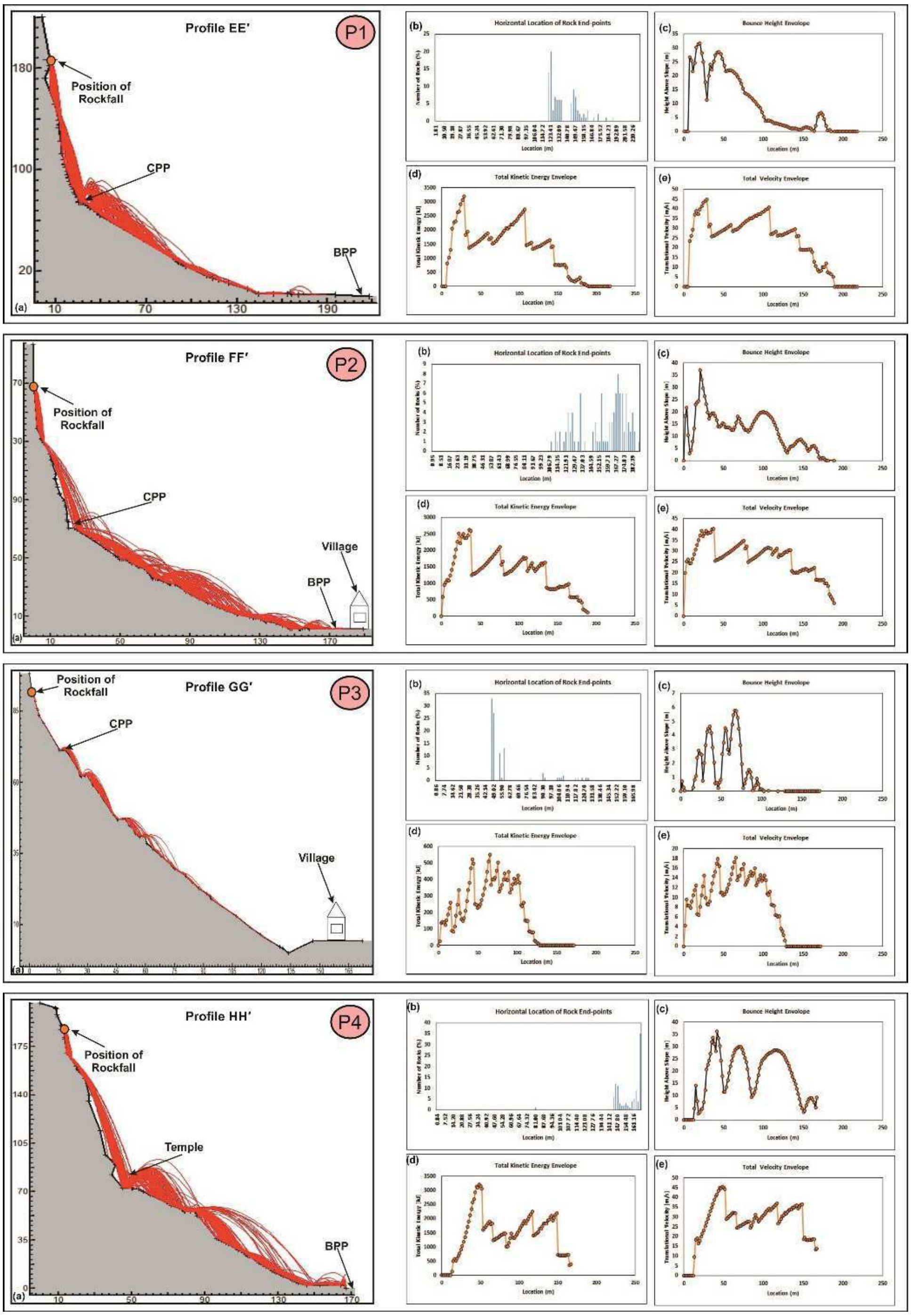

Fig.3. Rockfall analysis for profile EE' to HH': **(a)** trajectory path; graph of **(b)** runout versus distance; **(c)** bounce height versus distance; **(d)** maximum kinetic energy versus distance; **(e)** translation velocity versus distance.

profile OO' and highest value for NN'. The possible explanation for the lowest value of kinetic energy for profile OO' could be the gentle slope geometry in acceleration zone as compare to other two profiles.

Zone#08: Profiles II', JJ', KK' and LL' are four profiles in zone#08. In case of profile II', two rock blocks launching locations have been chosen for the analysis shown in Fig. 8(P15). The slope geometry for profile II' is such that it stopped all the rock blocks, started from the top of the slope. Therefore, another rock blocks launching location was considered to complete the analysis. Moreover, the analyses showed that in each profile the rock blocks hit, either directly the CPP or partially touched it. The results of the analyses have been shown in Fig. 8(P15-P18) and tabulated in Table 2.

3D Rockfall Analysis

2D rockfall analyses was performed along pre-defined slope profiles and neglects the effect of the topography. 3D rockfall analysis accounts the lateral dispersion of rockfall trajectories (Crosta and Agliardi, 2004), i.e., the ratio of the lateral distance separating the extreme fall paths to the slope length (Azzoni et al. 1995). To incorporate lateral separation in the rockfall analysis, 3D rockfall analysis has been performed using Rockfall Analyst tool, an ArcGIS extension (Lan et al., 2007). The program includes two parts (i) simulation of 3D rockfall trajectory and (ii) spatial distribution of rockfalls using raster modelling. The program is based on the lumped mass approach that provides at each cell of the considered DEM, the spatial frequency of runout, kinetic energy and rebound height.

The key input parameters for 3D rockfall trajectory analysis are

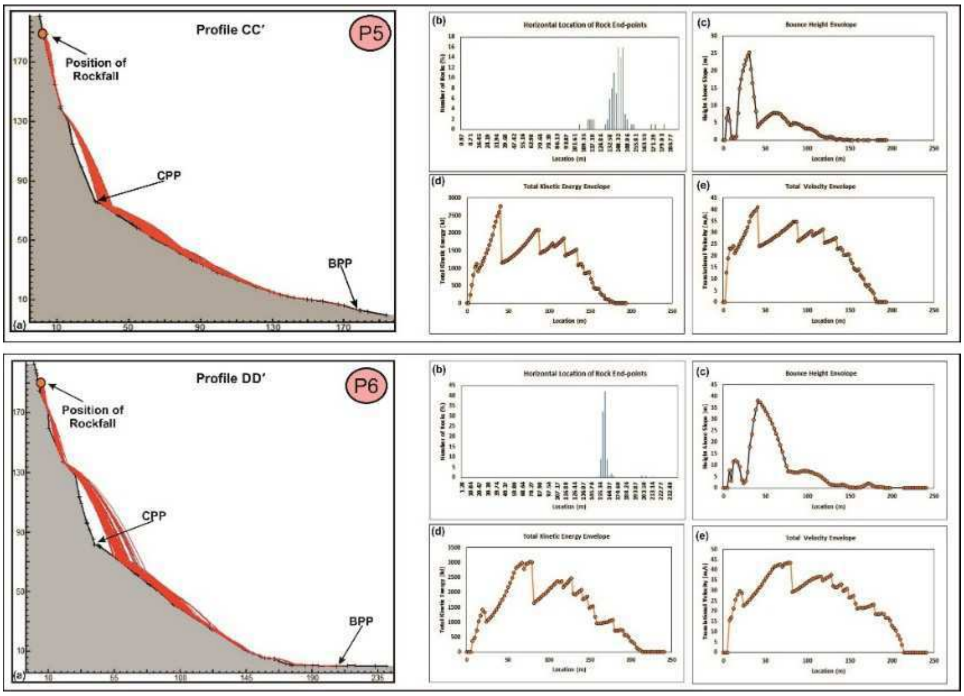

Fig.4. Rockfall analysis for profile CC' and DD': **(a)** trajectory path; graph of **(b)** runout versus distance; **(c)** bounce height versus distance; **(d)** maximum kinetic energy versus distance; **(e)** translation velocity versus distance.

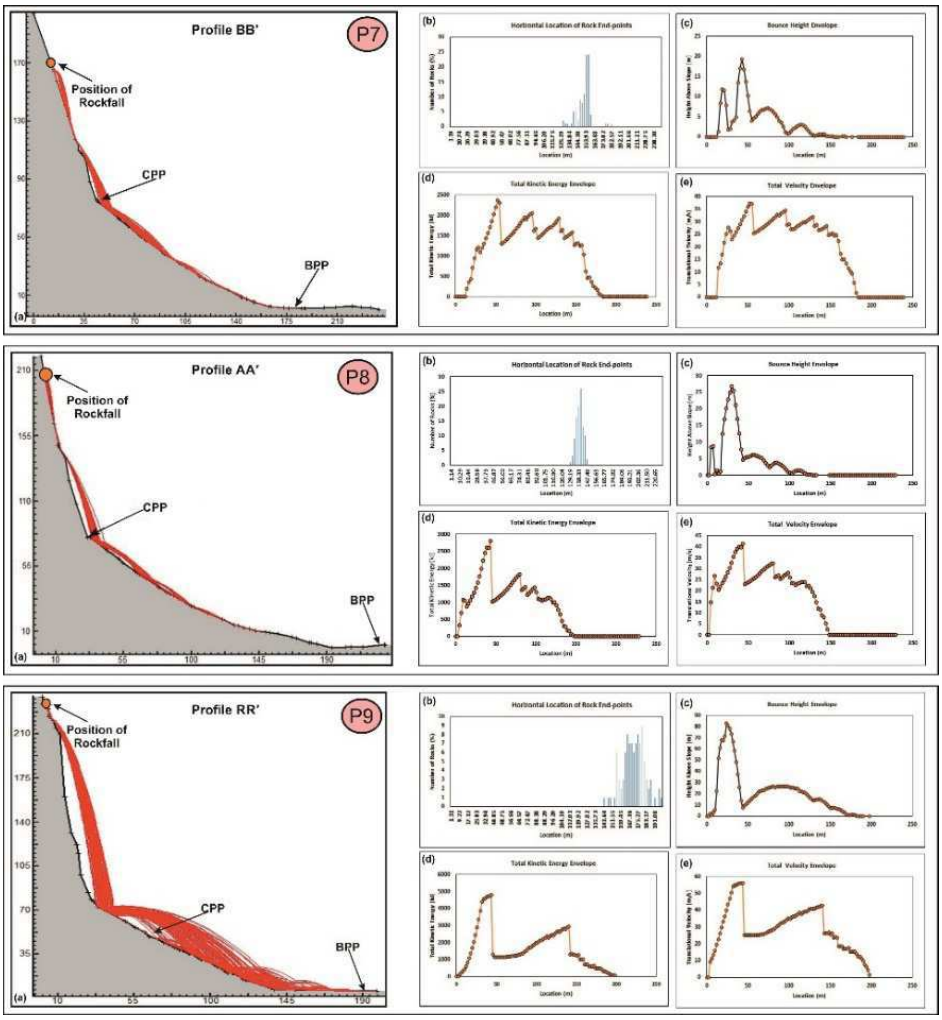

Fig.5. Rockfall analysis for profile BB', AA' and RR': **(a)** trajectory path; graph of **(b)** runout versus distance; **(c)** bounce height versus distance; **(d)** maximum kinetic energy versus distance; **(e)** translation velocity versus distance.

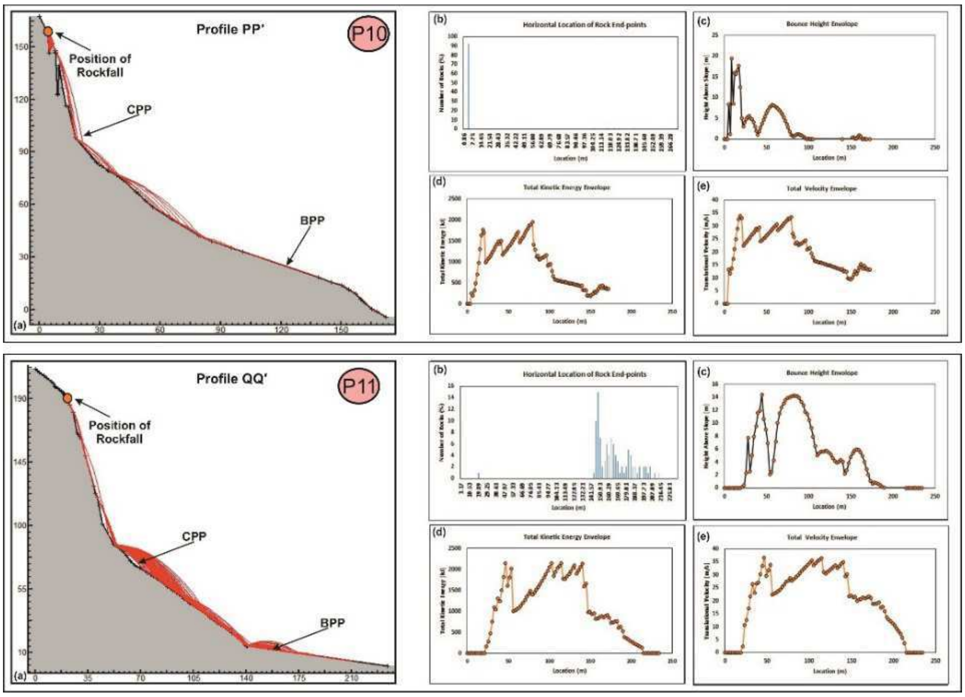

Fig.6. Rockfall analysis for profile PP' and QQ': **(a)** trajectory path; graph of **(b)** runout versus distance; **(c)** bounce height versus distance; **(d)** maximum kinetic energy versus distance; **(e)** translation velocity versus distance.

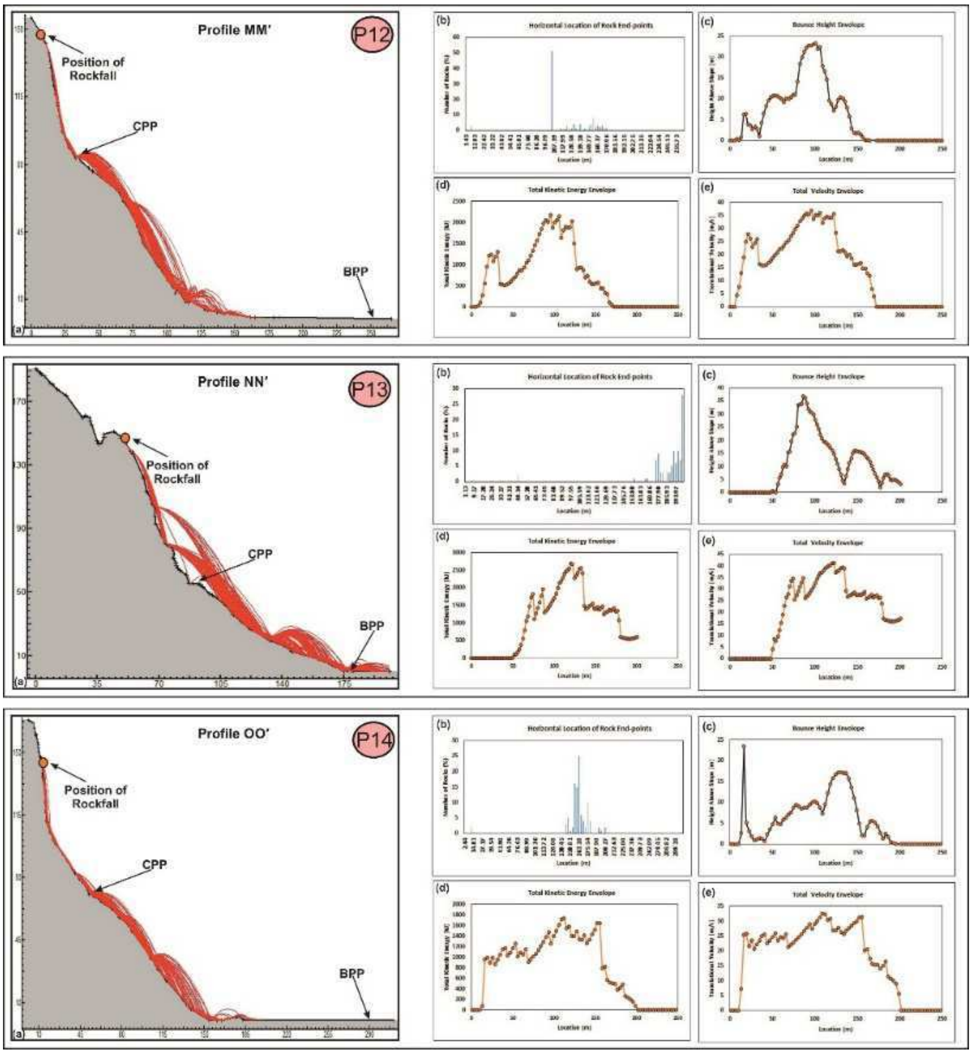

Fig.7. Rockfall analysis for profile MM', NN' and OO': **(a)** trajectory path; graph of **(b)** runout versus distance; **(c)** bounce height versus distance; **(d)** maximum kinetic energy versus distance; **(e)** translation velocity versus distance.

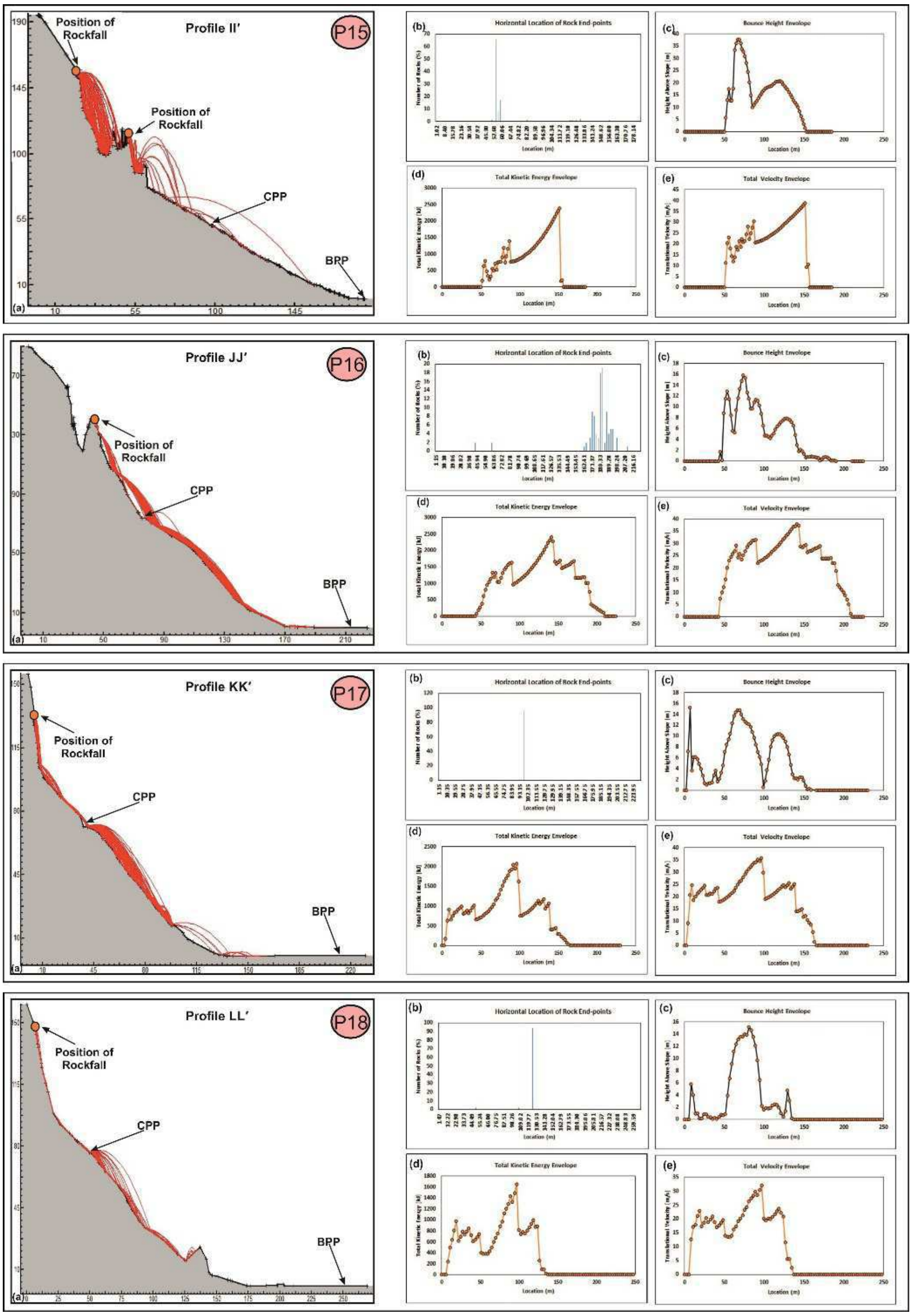

Fig.8. Rockfall analysis for profile II' to LL': **(a)** trajectory path; graph of **(b)** runout versus distance; **(c)** bounce height versus distance; **(d)** maximum kinetic energy versus distance; **(e)** translation velocity versus distance.

DEMs, rock fall seeders (sources), and slope (ground) surface properties such as slope angle and slope roughness. DEMs have been used for surface topography as well as for the preparation of aspect and slope raster maps. These maps have been used as an input raster data for rockfall analysis. Locations of rockfall sources, i.e. seeders are stored in shape files and can be defined as points or polyline features. Also, their properties are defined by user input if all seeders hold the same properties, or by an attribute table attached to the seeder shape file if each individual seeder has its own properties. 3D simulations allow the users to throw many rock blocks at each rockfall source (seeders) with different initial directions in order to mimic the uncertainties of rockfall sources. Surface material properties are stored in a polygon shape file. The coefficients, including normal restitution, tangential restitution and friction angle, are stored in the different fields of the shape file's attribute table. The properties from related fields of the attribute table will be read automatically during a physical rockfall simulation process. The resultant rockfall trajectories and their velocity features are saved as 3D polyline shape files. Together with the DEM, they are used as input for the raster modeling of rockfall characteristics, including spatial frequency, bounce height and energy.

Outcome of 2D and 3D Rockfall Analysis

The rockfall analysis indicated that most of the rock bocks fall on CPP, barring a few which fall on BPP. The analysis also indicates that the bounce height of the fallen rock block varies from 5.79m to 82.96m. The maximum kinetic energy of the fallen rock block has a value of

Table 2. Result of 2D Rockfall Analysis

Zone	Profile No.	Profile	Max. Runout Distance (m)	Max. Bounce Height (m)	Max. Kinetic Energy (kJ)	Max. Translation Velocity (m/s)
#01	P1	EE'	188.550	31.62	3201	40.20
	P2	FF'	188.055	37.14	2629	18.12
	P3	GG'	128.140	5.79	549	45.54
	P4	HH'	166.165	36.15	3215	38.98
#02	P5	CC'	180.970	25.25	2770	40.97
	P6	DD'	213.135	38.19	3020	43.47
#03	P7	BB'	181.616	19.31	2378	37.22
#04	P8	AA'	147.480	26.74	2800	41.39
#05	P9	RR'	197.010	82.96	4817	56.30
#06	P10	PP'	136.980	19.43	1949	33.89
	P11	QQ'	214.110	14.39	2152	36.68
#07	P12	MM'	170.000	23.32	2178	36.85
	P13	NN'	199.990	36.97	2693	41.36
	P14	OO'	200.260	23.45	1738	32.42
#08	P15	II'	155.990	37.74	2398	38.01
	P16	JJ'	209.440	15.81	2413	38.01
	P17	KK'	164.450	15.25	2077	35.74
	P18	LL'	133.210	15.17	1653	32.09

549kJ to a high value of more than 4000kJ. Similarly, the maximum velocity of the fallen rock block varies from 18.12m/s to 56.30m/s. Based on the kinetic energy of the fallen rock blocks, the SGT hill can be divided into the following three categories:

Kinetic Energy value >3000kJ: Rock blocks only partially touched the CPP and reached BPP due to high kinetic energy value. This condition is demonstrated by four profiles, i.e., EE', DD', HH' and RR' of respective zones. Moreover, it is noted that no rock blocks were able to knock CPP for profile DD, however, others profiles were able to partially hit CPP.

Kinetic Energy value 2000-3000kJ: Rock blocks hit the CPP and most of the rock blocks from different profiles reached to BPP. Also, profiles AA', CC', NN', FF', JJ', II', BB', MM', QQ' and KK' with decreasing kinetic energy satisfied this category. In addition, for profiles MM', II', JJ' and AA', the rock blocks were not able to reach BPP.

Kinetic Energy <2000kJ: Rock blocks did not reach BPP due to comparatively low kinetic energy. Four profiles were identified in this category, i.e. PP', OO', LL' and GG'. The rock blocks touched only CPP in case of profiles OO', LL' and GG'. However, in case of section PP', rock blocks reached BPP, though the bounce height is zero indicating either sliding or rolling motion of the rock blocks. The reason for rock blocks reaching BPP for these profiles could be attributed to the geometry of the slope profile that increases the kinetic energy in the later part of the simulation. The least kinetic energy was observed for profile GG' and could be due to gentler slope in comparison to all other profile sections.

Energy maps have also been prepared for both 2D and 3D analyses as shown in Fig. 9(a)-(b), and indicate that most of the kinetic energy is concentrated between the two-parikrama paths, thereby causing risk to the life of pilgrim performing parikrama. All these outputs tabulated in Table 2 indicate that the rockfall is a major risk to the life of the pilgrims at SGT hill. These energy maps further used to identify the location of suitable rockfall remedial measures.

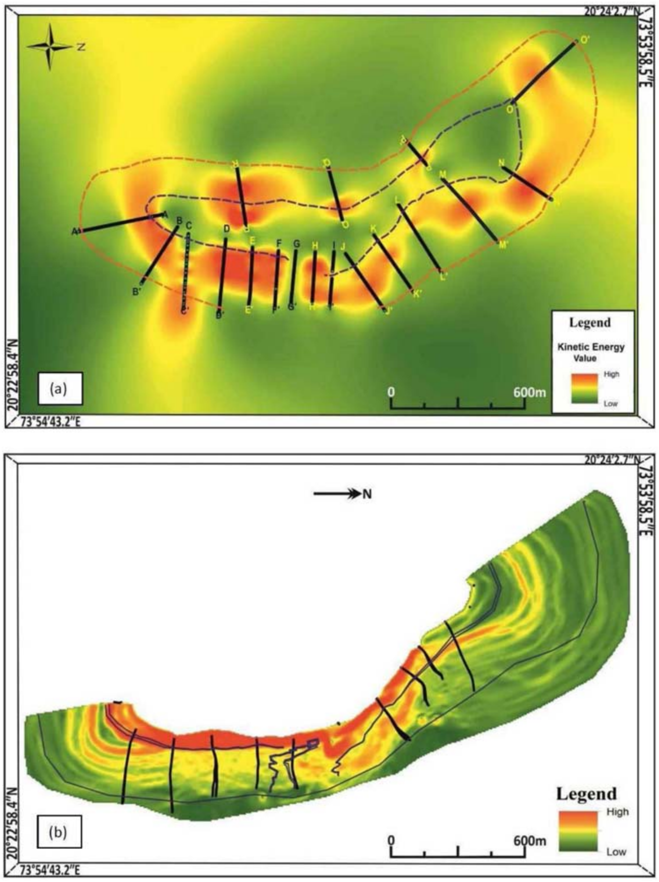

Fig.9. Energy Map showing concentration near the parikrama path **(a)** derived from 2D Rocfall program **(b)** derived from 3D Rockfall Analyst program.

REMEDIAL MEASURES

It is worth mentioning that the study area experiences rockfall problem, especially in rainy season and thus it needs to be addressed appropriately for a smooth parikrama by the devotees. The presence of more than two joint sets created structural failures and resulted in rockfall(s). So, the study area needs remedial measures to address the existing rockfall problem and efforts should be made either to stop the risk of rockfall or to minimize it. However, the space constraints limit the protection measures, especially at CPP. Hence, a combination of active and passive stabilization and protection methods have been recommended. These methods include re-sloping, scale and trimming of loose rock blocks causing rockfall along with cleaning of slope with pressurized water prior to application of drape meshing along with rock-bolt and shotcrete. It is to be noted that some of the proposed protection measures have already been installed in some part of the SGT hill and it has stopped/minimized the rockfall(s) (Fig. 10). Also, a brief description of drape mesh and rock bolt used on-site are given below:

Drape Mesh

Double twisted (DT) steel wire has been proposed as a rockfall netting. The advantage of DT mesh over single twist (chain-like) mesh is that the damage to a DT mesh remains local and the mesh does not unravel, even in the event of some of its wire accidental breaking due to the double twist 'locked yet flexible' connection between adjacent wires. The steel wire used for double twisted wire mesh is galvanized with Zn coating (Fig. 10d). Also, the mesh shall be reinforced with cables to contain boulders of larger size and mass. These cables reinforced mesh is known as Steel Grid and provide high tensile strength at low strain. For SGT hill site, high energy absorption (HEA)

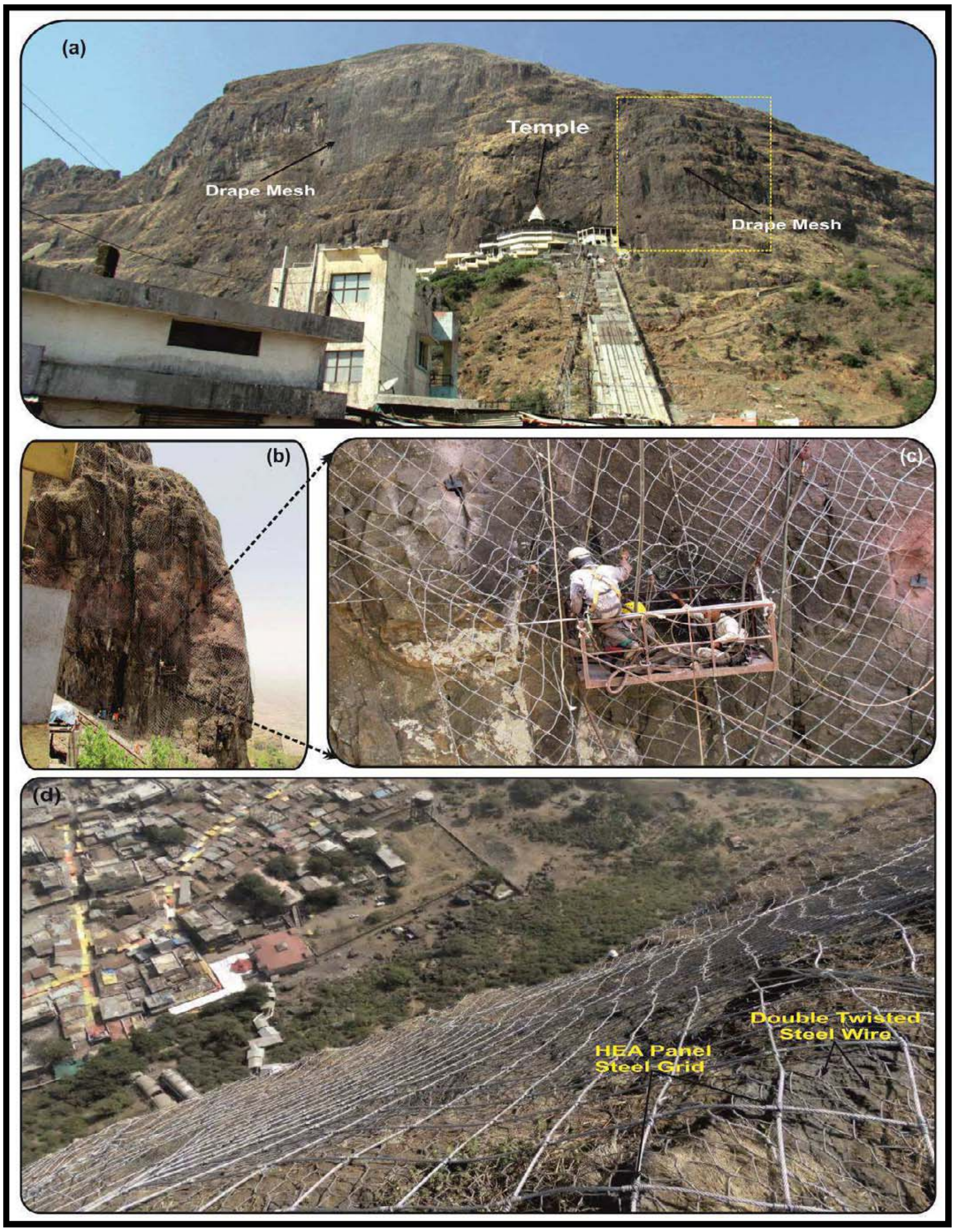

Fig.10. Proposed rockfall mitigation measures: **(a)** Implementations of drape mesh, **(b)** in-large part of yellow rectangle in **a**, **(c)** workers installing drape mesh along with rockbolts, **(d)** installed double twisted steel wire and HEA panel steel grid.

panel steel grid has been proposed. The HEA panel is woven from a single continuous length of high tensile strength steel wire rope, joined at each crossing point with the HEA double knot connection. The steel wire knot diameter should be 3.00mm to 3.5mm. The intersection points should be reinforced to resist for static and dynamic stress for the deformation of the panel. HEA panel is advice to work in conjunction with rock-bolts to increase the stability of the unstable surficial layer of the rock (Fig. 10d).

Rock Bolts

A number of rock-bolts are also proposed wherever found necessary on the SGT hill surfaces. Rock-bolts are comprising of 32mm diameter galvanized steel bars of 3m length or greater with bolting pattern of 1.5m*1.5m (and/or spot bolting) with the minimum yield stress of the rockbolt of 500N/mm^2 (Fig. 10c).

Locations vulnerable to erosion near the base of the SGT hill slope, steel fiber reinforced shotcrete(SFRS) has been proposed to provide addition protection to the temple. Steel fibres should be of Wirand FS 9 type or equivalent. They are made of high tensile strength cold drawn wire and cut in standard lengths with end deformations to ensure best anchorage in the concrete matrix and thereby ensuring better post crack strength.

CONCLUSIONS

For the present study following con conclusions can be drawn:

1 Field observations helped in identification of the problem of rockfall at SGT and also the problem has been confirmed by 2D and 3D rockfall analysis.

2 2D rockfall analyses indicate that the most of the rock blocks fall on CPP while some have fallen on BPP, indicating the risk from rockfall to the pilgrims performing the parikrama. Also, based on kinetic energy values of the fallen rock blocks, the SGT hill was divided into three categories: viz. (i) kinetic energy value >3000kJ; (ii) kinetic energy value 2000-3000kJ, and (iii) kinetic energy <2000kJ.

3 Energy maps have been prepared for both the 2D and 3D analyses, and they indicate that most of the kinetic energy is concentrated between the two parikrama paths, thereby causing risk to the life

of pilgrim due to rockfall. These maps, then further used to propose suitable protection measures from rockfall.

4 A combination of active as well as passive mitigation measures has been proposed for SGT hill. Double twisted (DT) steel wire has been proposed as a rockfall netting and the mesh has been reinforced with high-energy absorption (HEA) panel steel grid to contain boulders of larger size and mass. Also, a number of rock-bolts are also proposed comprising of 32mm diameter galvanized steel bars of 3m length or greater with a bolting pattern of 1.5m*1.5m for planar and wedge failures.

5 It is to be noted that some of the proposed protection measures have already been installed in some part of the SGT hill and it has stopped/minimized the falling of rocks. For the first time rockfall hazard assessment was made in such a detail to a site and suggestions made are implemented by the State Government for the protection of the temple as well as the life of pilgrims from the rockfall.

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