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REDUCTION OF ROCKFALL RISK OF THE TELEFERIK AREA OF SANTORINI - GREECE.

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Abstract

The Teleferik area of Santorini Volcanic Complex, is characterized by rockfall risk due to existing morphological, geological, geotechnical and geodynamic conditions. It is therefore considered a high risk area because of the huge number, in annual base, of its visitors. The objects of the research are: (i) To identify areas with increased risk of boulders' detachment, ii) The mapping of rockmasses for direct intervention projects,(iii)To suggest scenarios of rockfall events, (iv) To recommend the urgent works required upslope of the lower lift station of the Teleferik in order to reduce the existing risks to an utmost minimum. The calculations for the above assessments were mostly based on back analysis method, processing data of the recent rockfall events. The proposed interventions belong to the general context of large-scale projects, while top priority is given to works upslope of the lower lift station, which will work as an extra last line of defense in case of large-scale geodynamic events in the future.

Key words: *Rockfalls, Hazard, Santorini, Hellas.*

Περίληψη

Η περιοχή της καλδέρας της Σαντορίνης, ανάντη του τελεφερίκ και του Παλαιού λιμένα Φηρών, χαρακτηρίζεται από υψηλό κατολισθητικό κίνδυνο λόγω των υφιστάμενων μορφολογικών, γεωλογικών, γεωτεχνικών και γεωδυναμικών συνθηκών. Δεδομένης της διέλευσης εκατοντάδων χιλιάδων τουριστών σε ετήσια βάση, γίνεται εύκολα αντιληπτή η αναγκαιότητα λήψης συγκεκριμένων μέτρων μείωσης του κινδύνου. Η έρευνα έχει ως στόχους: i)Την υπόδειξη περιοχών με αυξημένη πιθανότητα εκδήλωσης αποκολλήσεων βραχοτεμαχών ii) Την υπόδειξη των όγκων στους οποίους θα πρέπει να γίνει άμεση παρέμβαση, iii) Την παρουσίαση σεναρίων κατολισθήσεων – καταπτώσεων, iv) Την υπόδειξη επειγόντων έργων ανάντη του κάτω Σταθμού του Τελεφερίκ προκειμένου να μειωθεί στο ελάχιστο δυνατό η επικινδυνότητα. Χρησιμοποιήθηκε γνωστό λογισμικό ανάλυσης καταπτώσεων, με το οποίο έγιναν ανάδρομες επιλύσεις και προσομοιώσεις σύμφωνα με τα στοιχεία από πρόσφατα φαινόμενα. Οι παρεμβάσεις εντάσσονται στο γενικότερο πλαίσιο των έργων μεγάλης κλίμακας, ενώ δίνεται ιδιαίτερη έμφαση στα προτεινόμενα επείγοντα έργα ανάντη του κάτω Σταθμού Τελεφερίκ, τα οποία θα λειτουργήσουν ως πρόσθετη δικλείδα ασφαλείας σε περίπτωση εκδήλωσης έντονων κατολισθητικών γεγονότων.

Λέξεις κλειδιά: *Κατολίσθηση, Κίνδυνος, Σαντορίνη, Ελλάδα.*

1. Introduction – Background - Scope

The area of Teleferik - Old Port of the island of Thera presents an increased rockfall risk which is expressed by numerous events, occurring on the slopes of the caldera (Figure 1).

The high rockfall risk is due to a combination of factors and in particular: (i) the steep slopes and existing morphological discontinuities, (ii) the vertical primary and secondary discontinuities, that intersect the volcanic formations, (iii) the combination of geological and geotechnical conditions and particularly the succession of the rocky and loose formations, (iv) the earthquake and volcanic activity, (v) the severe weathering and (vi) the human interventions (Lekkas, E., 2009a).

Since, during the last decades, the area is attracting more than one million visitors per year, a number of effective projects has been implemented, in order to address rockfall events (Damala, et al., 1994).

Over the last few years due to: (i) the intense geodynamic processes and the subsequent weathering of rockmass, (ii) the increasing number of visitors and (iii) the occurrence of severe events, extensive research has taken place (Lekkas, E. 2009b), in order to propose the required works, construction of which, is expected to begin in November 2013.

However at the end of February 2012, there has been a rockfall event of a volume of 0.5 m^3 from the North slope which broke into the building of the Lower Station of the Teleferik, fortunately causing damage only in the waiting room and other facilities of the building. From the fieldwork it was found that there are more blocks in various parts of the slopes, prone to wedge – planar or toppling failure. Based on this fact, there has been an in-situ research project in order to determine the appropriate, urgent measures against rockfall hazard in the area, until the construction of the aforementioned large scale works starts.

This research aims to:

- Identify the boulders with increased rockfall risk.
- Present rockfall simulations in areas of increased probability of failure.
- Designate the necessary rockfall protection measures over the Lower Station which are required in order to reduce the existing risk.

Figure 1 - General view of the study area. The Teleferik line is marked with a dotted line, Fira appears on the upper part of the slope and the Old Port appear at the Lower part of the slope.

2. Design Criteria

Based on data from previous surveys (Druitt, Th, et al., 1999, Lekkas, E., 2009b, Antoniou, A. & Lekkas, E., 2010, Rathmayr, B., et al., 2012), fieldwork and consideration of all the evidence, nine areas have been identified where a rockfall could possibly start (Figure 2, 3). The design data are presented in Tables 1, 2. Five of these areas are located on the northern slope (N-A to N-E) and four in the southern slope (S-A to S-D). The parameters and design criteria are described below.

2.1. Parameters for calculating size of unsafe boulders

The size of unsafe boulders varies, as it primarily depends on the geological - geotechnical characteristics of the rockmass. It should be noted that detailed geological – geotechnical mapping of the area exist at a scale of 1:500 (Lekkas E., 2009b). The parameters (Table 1, 2) that were taken under consideration are:

- The unsafe boulders of Rhyodacitic Lava of Thirasia (TL) are large in volume, which can reach up to 30 m^3, since the average distance between vertical discontinuities, as well as the distance between horizontal discontinuities are 5 and 6 m respectively, where the undermining of the slope takes place.
- For the formation of Basaltic Andesitic Lava of Scaros (SL) the boulders volume is smaller and can reach up to 15m^3, since the average distance between vertical discontinuities, as well as between horizontal discontinuities, are 3 and 5 m respectively.
- For the formation of bedded and breccia Tuffs (T) as well as for the formations of Black Pumice and Ignimbrite (BP and IGN) the boulders volume is less than 5 m^3.

Consequently, the maximum weight of blocks which might be detached from the formation of Rhyodacitic Lava of Thirasia (TL) was estimated at 77 tn, while the blocks weight of Basaltic Andesitic Lava of Scaros (SL) formation was estimated at 33 tn. The blocks weight for the formation of bedded and breccia Tuffs (T) was considered to be 5 tn. As an input parameter for the analysis, it was considered only the 1/3 of the values above, because of the “cracking” of the boulders due to impacts along their route.

2.2. Terrain parameters

The following parameters were taken under consideration (Table 2):

- The altitude at which the volume is located, the horizontal distance that the block will traverse, while additional importance is given to the topographic profile from the starting to the “impact” point (i.e. building of the Lower Station).
- The friction angle φ of the geological formation, the vertical and tangential coefficient of the material Rn and Rt respectively (natural and geomorphological feature) as well as the standard deviation of these values.

2.3. Capacity of absorbing Energy of the intermediate area

The intermediate area, from the starting point of the rockfall to the Lower Station has a variable capacity to absorb the total kinetic energy of the falling blocks, depending on the nature of the formation on the slope surface. The absorbing capacity is divided into high, medium and low (Table 1).

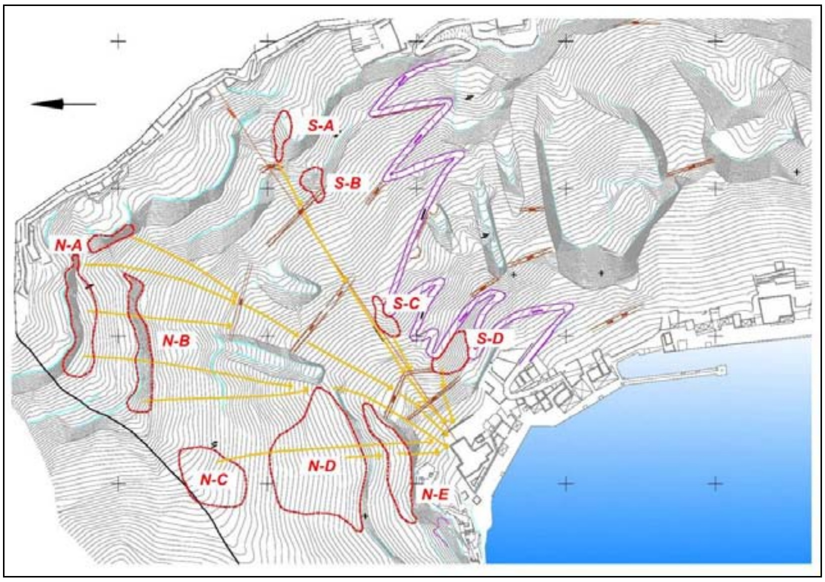


Figure 2 - Map with the locations –areas at the North (N-A to N-E) and South (S-A to S-D) slopes where it is highly likely that landslide phenomena may occur

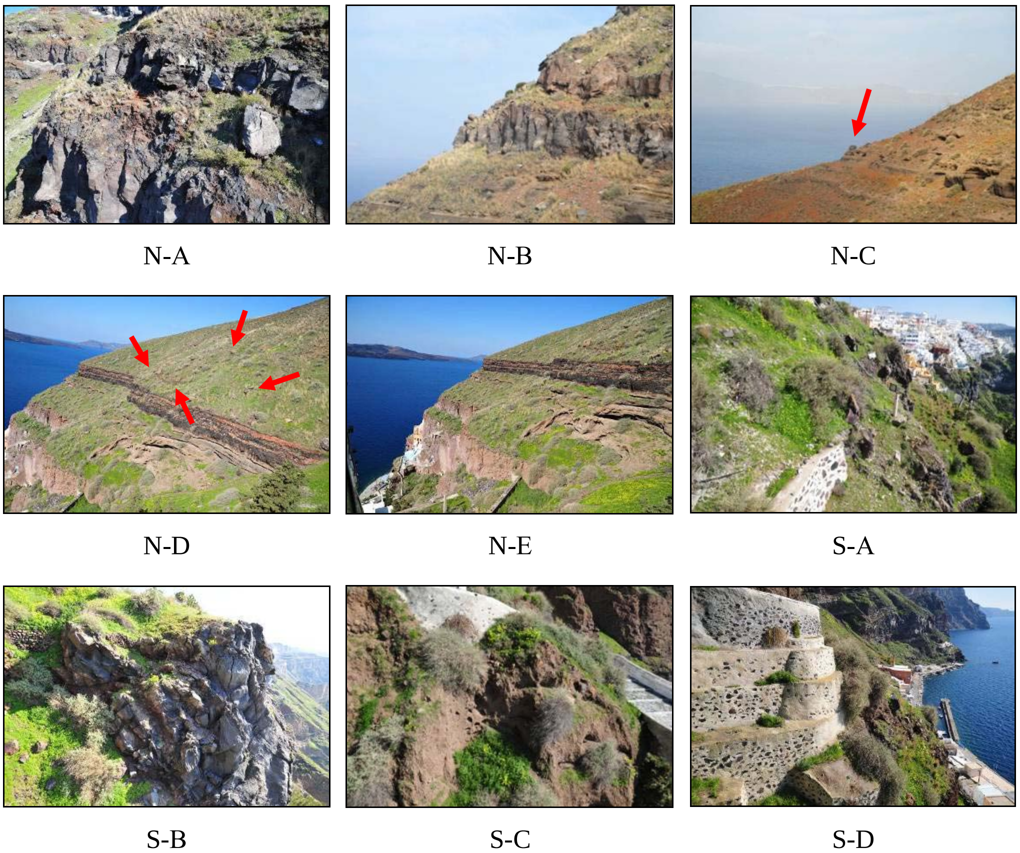


Figure 3 - Hanging boulders corresponding to the areas N-A to N-E and S- A to S-D.

Table 1 – Parameters for calculating size of unsafe boulders

Area	Formation Type	Max Volume (m^3)	Height (m)	Horizontal Distance (m)	Hazard Estim.	Damping	Risk for the Lower Station
N-A	TL	30	220-240	300	High	High on scree	Mean
N-B	SL	20	170-180	250	High	High on scree	Mean
N-C	T	5	120-150	150	High	Low	High
N-D	SL	5	80-100	100	High	Low	High
N-E	BP, IGN	5	40-80	50	High	Low	High
S-A	TL	30	200-240	300	High	High on scree	Mean
S-B	SL	8	130-150	250	High	High on scree	Mean
S-C	SL	2	70-90	70	High	High	Mean
S-D	IGN	2	40-50	30	High	Low	High

Table 2 – Terrain parameters

Description	Unit	Friction Angle φ	Vertical Coefficient Rn		Tangential Coefficient Rt	
			Mean Value	Standard Deviation	Mean Value	Standard Deviation
Tuffs	T	24	0.20	0.04	0.70	0.04
Lava	SL	30	0.30	0.04	0.75	0.04
Lava	TL					
Ignimbrite	IGN					
Black Pumice	BP					
Scree	TSC	30	0.32	0.04	0.82	0.04
Asphalt	B	30	0.40	0.04	0.90	0.04

3. Risk of Lower Station

The risk of Lower Station derives from the combination of existing risk per specific risk areas (N-N-A to N-E and A to S-D) and the 'absorbing energy' capacity along the boulder's travelling downwards, until they reach the lower morphological section. In particular, the risk derives from the equation:

$$Risk = Hazard \times 1 / Absorbing\ Capasity$$

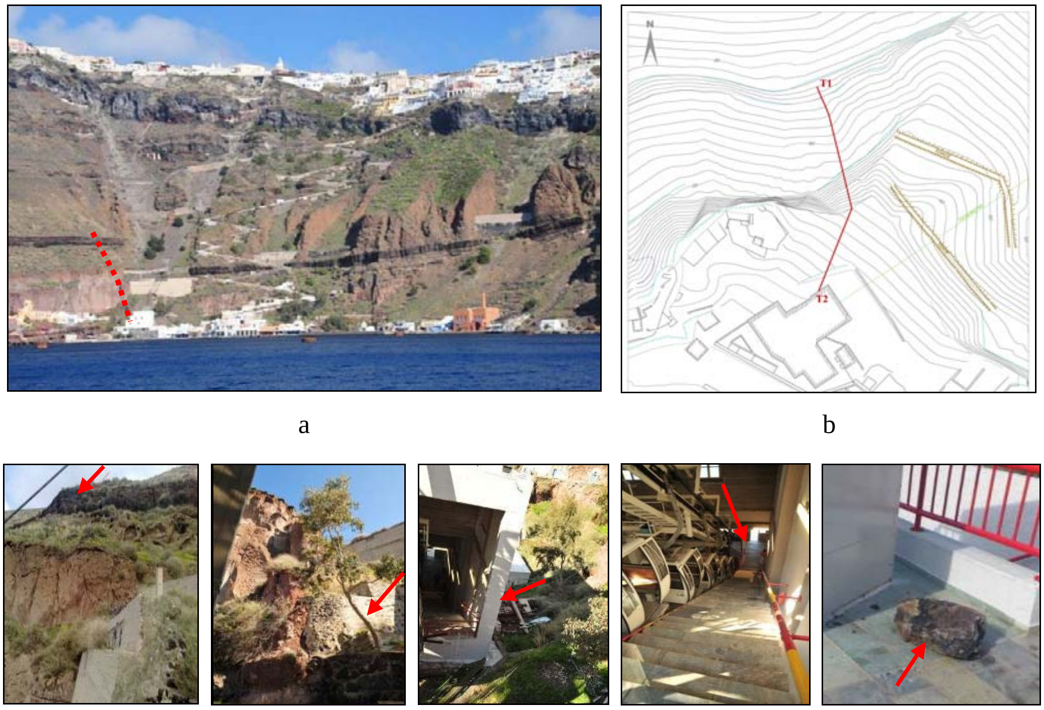
Based on the above, it is possible to estimate the risk of Lower Station for any rockfall starting point (Table 1).

4. Rock fall event of February 2012

As it has been previously stated, in February 2012 a boulder was detached from the North Slope and finally crashed inside the building of the Lower Station causing material damage to the facilities. The volume of the boulder, which was detached from the Black Pumice formation over the Lower Station, was estimated at about 0.5m^3 and after it bounced on various parts of the slope, it landed inside the Lower Station (Figure. 4).

Analyses of the observed rock fall event were executed, based on the data of the original volume, the morphological profiles and its route on the slope, using the software Rocfall by Rocscience Ltd (Figure 5a, 5b, 5c, 5d).

The vertical and tangential coefficients, Rn and Rt respectively (natural and geomorphological characteristics), as well as the standard deviation of these values which are presented in Table 2 and concern each geotechnical section have been assessed, by using the backup analysis method.



a b c d e f g

Figure 4 - The route of the Black Pumice rock boulder that was detached (a,b) and landed at the Lower Station of the Teleferik (c-g).

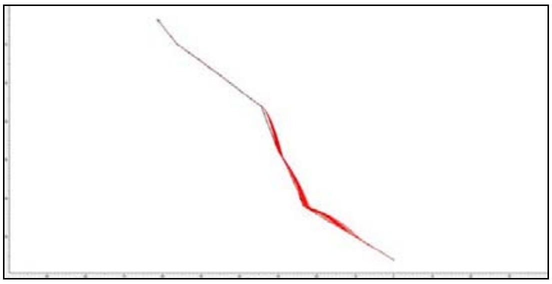


Figure 5a - Trajectory of the Black Pumice rock boulder at section T1-T2.

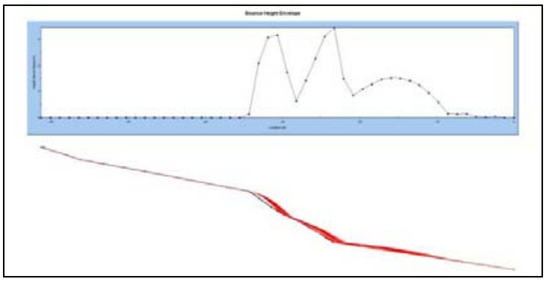


Figure 5b - Variation of bounce height of Black Pumice boulder at section T1-T2.

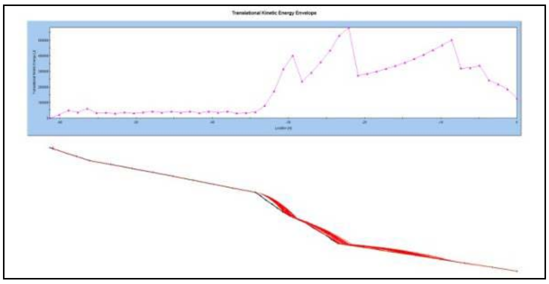


Figure 5c - Kinetic Energy Envelope for falling boulders at section T1-T2.

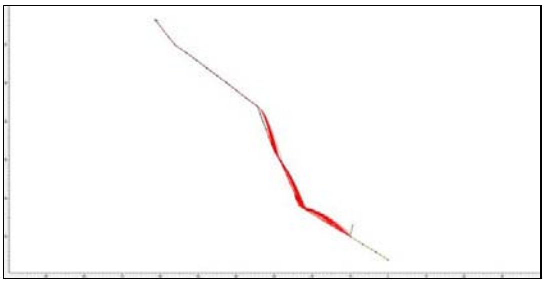


Figure 5d - Trajectory of Black Pumice rock boulder with rock fall barrier system at section T1-T2.

5. Rock fall analysis – Suggested protection measures

Based on the collected data, simulations have been made for the three high risk areas of the north slope, (N-C, N-D, N-E) and one high risk area of the south slope (S-D). It should be noted that there are not many incidents of rockfall events of volcanic formations, available in international bibliography. For this reason, coefficients Rn and Rt have been used based on the data of the backup analysis. The input data are:

- The geometry of the terrain has been assessed from the representative cross sections which were selected in relation to the areas designated as potentially unstable.
- The geotechnical characteristics of the geological formations which appear on the surface of the slope. The geological formations encountered in the area are divided into sub-sections (Table 1, 2), with different design input values.
- Parameters which characterize the terrain, such as the friction angle of the material φ, the vertical and tangential coefficients Rn and Rt respectively (natural and geomorphological features) and the standard deviation of these values (Table 1, 2).
- The characteristics of the boulders, such as the Weight W (kg) =Volume V (m^3) * Specific Weight γ (kN/m^3), the initial speeds at the time of detachment (horizontal and vertical) and the standard deviations of these values.

Rockfall simulations were conducted at each location (Tracks of Falling Blocks, Kinetic Energy and Bounching Height Diagrams). Based on the simulation data, the maximum capacity of the required Rock Fall Barrier from the North side of the Lower Station is estimated at 1000kJ at 4 meters height. From the South side of the Lower Station the maximum capacity of the Rock Fall Barriers is estimated at 500kJ at 3 meters height. For safety reasons the values above, have been doubled.

The layout of the Rock Fall Barriers, after on site investigation of the application areas of the selected systems is shown in Figures 6a, 6b.

In total, three Rock Fall Barriers are suggested as follows:

- Between the Lower Station and pillar No 1, crosswise to the route of Teleferik with the following features: Length: 20m, Height: 3m, Capacity : 1000kJ.
- On the side of the Lower Station, upwards at a 60 degrees angle relative to the direction of the Teleferik lines with the following features: Length: 10m, Height: 4m, Capacity : 2000kJ.
- On the side of the Lower Station, downwards at 60 degrees angle, relative to the direction of the Teleferik lines with the following features: Length: 10m, Height: 4m, Capacity : 2000kJ.

a b c

Figure 6a - Views of the area showing the rock fall barriers systems a, b and c.

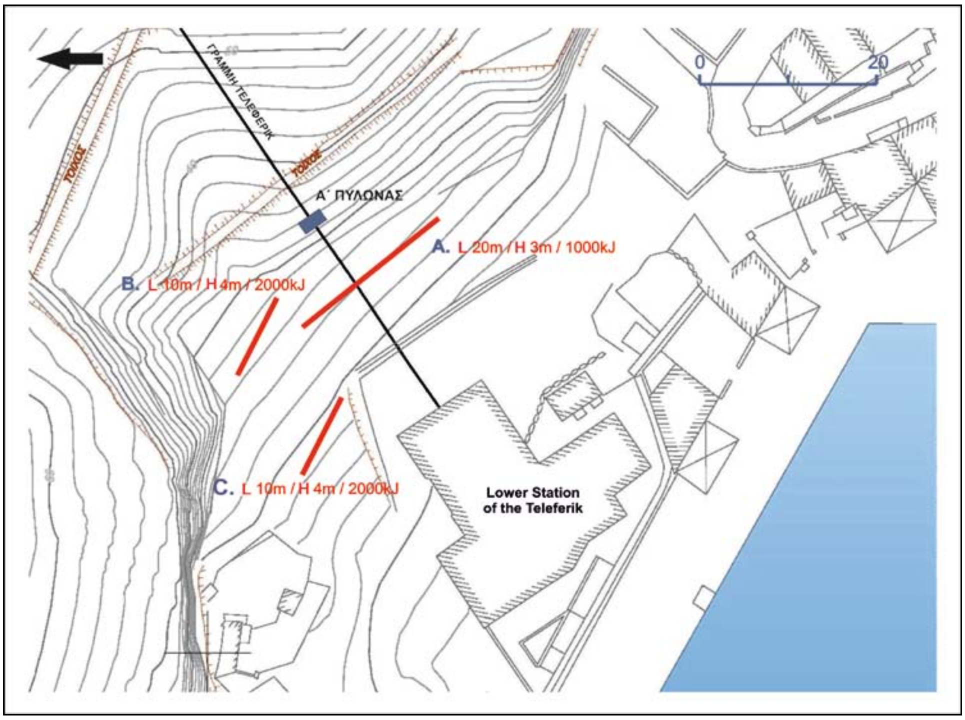


Figure 6b - Topographic diagram showing the layout of the proposed rock fall barriers (a, b, c) above the installations of the Lower Station of the Teleferik.

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