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Landslide Processes



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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 annual number of visitors. The aims of the research are: (i) to identify areas with increased risk of boulders' detachment, (ii) to map the rockmasses for direct intervention projects, (iii) to suggest scenarios of rockfall events, (iv) to recommend urgent works required upslope of the lower lift station of the Teleferik in order to reduce the existing risks to the minimum. The calculations were mostly conducted with back analysis and processing of data of 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.

Keywords

Rockfall • Hazard • Santorini • Greece

23.1 Introduction: Background—Scope

The area of Teleferik—Old Port of the island of Santorini presents an increased rockfall risk, which is expressed by numerous events occurring on the slopes of the caldera (Fig. 23.1).

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 2009).

Since, during the last decades, the area is attracting more than one million visitors per year, numerous effective projects have been implemented to address rockfall events. Over the last few years extensive research has taken place (Lekkas 2009), because of to the intense geodynamic processes and the subsequent weathering of rockmass, the increasing number of visitors and the occurrence of severe events, in order to propose the required works, the construction of which is expected to begin in November 2013.

However at the end of February 2012, a rockfall event of 0.5 m³ volume took place, which broke into the building of the Lower Station of the Teleferik, fortunately causing only material damage to the waiting room and other facilities of the building. From fieldwork it was found that there are more blocks in various parts of the slopes that are prone to wedge—planar or toppling failure. Based on this fact, an in situ

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Fig. 23.1 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 appears at the *Lower part* of the slope

research project began in order to determine the urgent measures against rockfalls in the area, until the construction of the large scale works starts.

This research aims to: (i) identify the boulders with increased rockfall risk, (ii) present rockfall simulations in areas of increased probability of failure, and (iii) designate the necessary rockfall protection measures over the Lower Station which are required in order to reduce the existing risk.

23.2 Design Criteria

Based on data from previous surveys (Druitt et al. 1999; Lekkas 2009; Antoniou and Lekkas 2010), fieldwork and consideration of all the evidence, nine areas have been identified where a rockfall could possibly start (Fig. 23.2). Five of these areas are located on the northern slope (N-1 to N-5) and four in the southern slope (S-1 to S-4). The parameters and design criteria are described below.

23.2.1 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 exists at a scale of 1:500 (Lekkas 2009). The parameters that were taken under consideration are shown in Table 23.1. The size of the boulders in relation with geological-geotechnical characteristics is described below.

- The unsafe boulders of Rhyodacitic Lava of Thirasia (TL) are large in volume, which can reach up to 30 m^3 . The average distance between vertical discontinuities and the distance between horizontal discontinuities, where the undermining of the slope takes place, is 5 and 6 m respectively.
- The boulders of Basaltic Andesitic Lava of Scaros (SL) are smaller in volume and can reach up to 15 m^3 . The average distance between discontinuities, vertical and horizontal, is 3 and 5 m respectively.



Fig. 23.2 Map with the areas at the North (N-1 to N-5) and South (S-1 to S-4) slopes where it is highly likely that landslide phenomena may occur and view of the hanging boulders corresponding to the areas N-2, N-4 and S-1

Table 23.1 Parameters for calculating size of unsafe boulders

Area	Formation type	Max vol. (m ³)	Height (m)	Horizontal distance (m)	Hazard Estim.	Damping	Risk for the lower station
N-1	TL	30	220-240	300	High	High on scree	Mean
N-2	SL	20	170-180	250	High	High on scree	Mean
N-3	T	5	120-150	150	High	Low	High
N-4	SL	5	80-100	100	High	Low	High
N-5	BP, IGN	5	40-80	50	High	Low	High
S-1	TL	30	200-240	300	High	High on scree	Mean
S-2	SL	8	130-150	250	High	High on scree	Mean
S-3	SL	2	70-90	70	High	High on scree	Mean
S-4	IGN	2	40-50	30	High	Low	High

- The boulders of bedded and breccia Tuffs (T) and Black Pumice and Ignimbrite (BP and IGN) are less than 5 m³ in volume.

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

23.2.2 Terrain Parameters

The following parameters were considered (Table 23.2):

- The altitude at which the boulder is located, the horizontal distance that the block will traverse and the topographic profile between the starting and 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, R_n and R_t respectively (natural and geomorphological feature), and the standard deviation of these values.

Table 23.2 Terrain parameters

Description	Unit	Friction angle ϕ	Vertical coefficient R_n		Tangential coefficient R_t	
			Mean value	Standard dev.	Mean value	Standard dev.
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

23.2.3 Capacity of Absorbing Energy of the Intermediate Area

The intermediate area between the starting point of the rockfall and the “impact” point at the Lower Station has a variable capacity to absorb the total kinetic energy of the falling blocks, depending on the nature of the formation of the slope surface. The absorbing capacity is divided into high, medium and low (Table 23.1).

23.3 Risk at the Lower Station

The risk at the Lower Station derives from the combination of existing risk per specific risk area and the ‘absorbing energy’ capacity of the boulders travelling downwards, until they reach the lower morphological section. The risk derives from the equation:

$$Risk = Hazard / Absorbing Capacity$$

Based on the above, it is possible to estimate the risk at Lower Station for any rockfall starting point (Table 23.1).

23.4 The Rock Fall Event of February 2012

In February 2012 a boulder was detached from the North Slope and crashed inside the building of the Lower Station causing material damage to the facilities. The original volume of the boulder which was detached from the Black Pumice formation over the Lower Station is unknown. However, the remaining boulder which landed inside the

Lower Station, after it bounced on various parts of the slope, was estimated at about 0.5 m³ (Fig. 23.3).

Analyses of the observed rock fall event were executed, based on the data of the original volume, the morphological profiles and the route on the slope, using the software RocFall by RocScience Ltd, version 4.0.

The vertical and tangential coefficients, R_n and R_t respectively (natural and geomorphological characteristics), and the standard deviation of these values (Table 23.2) have been assessed with the use of the back analysis method.

23.5 Rock Fall Analysis. Suggested Protection Measures

Based on the collected data, simulations have been made for three high risk areas of the north slope, (N-3, N-4, N-5) and one high risk area of the south slope (S-4). It should be noted that there are not many incidents of rockfall events of volcanic formations, available in international bibliography. For this reason, coefficients R_n and R_t have been used based on the data of the back analysis. The input data are: (i) the geometry of the terrain, (ii) the geotechnical characteristics of the geological formations, (iii) the friction angle of the material ϕ , the vertical and tangential coefficients R_n and R_t respectively and the standard deviation of these values, and (iv) the characteristics of the boulders.

Rockfall simulations were conducted at each location. Based on the simulation data, the maximum capacity of the required Rock Fall Barrier from the North side of the Lower Station was estimated at 1000 kJ at 4 m height and from the South side at 500 kJ at 3 m height. For safety reasons the values were doubled.



Fig. 23.3 The route of the Black Pumice rock boulder that was detached (a,b) and landed at the Lower Station of the Teleferik (c-f)



Fig. 23.4 Views of the area showing the rock fall barriers systems (a), (b) and (c)

The layout of the Rock Fall Barriers which was suggested after the onsite investigation of the application areas for the selected systems, is shown in Fig. 23.4.

In total, the installation of three Rock Fall Barriers was suggested as follows:

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

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