Landslide hazard and risk in geologically active areas. The case of the caldera of the Santorini (Thera) volcano island complex (Greece)

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ABSTRACT: The Santorini volcano island complex (Aegean Sea – Greece) represents a unique structure with dominant presence of the most impressive caldera in the world formed during the volcanic activity of the Minoan times (1644 BC). Due to high tourist activity and related development, and in order to determine safe land uses, the landslide hazard is determined along the caldera slopes based on geomorphological, geological and geotechnical criteria and according to human interventions. Based on the existing infrastructure, development and human activity an assessment of landslide risk is attempted in three levels, low, medium and high. This calibration is important since it prioritizes the areas that need interventions and necessary works in order to minimize the consequences.

1 INRODUCTION

The Santorini (Thera) island complex represents one of the most peculiar structures not only of the Hellenic region (Figs 1-2) but worldwide since it combines the following elements:

- The impressive geological – geodynamic processes and especially the geological structure and evolution of the volcanic complex.
- The existing geomorphological characteristics including the development of the largest caldera and the most impressive volcano in the world.
- The rich historical heritage with facts and works that are directly related to the volcanic activity from the prehistoric times to present.
- The architecture that dominates the majority of the residential constructions exhibiting special characteristics adjusted to the geological – geomorphological, physical – geographical and climatic regime of the area.

The above characteristics however are responsible for a significant tourist activity. Despite the fact that such activity has contributed a lot to the socio-economical development of the island during the past few decades at the same time it promotes dramatic pressure for land exploitation mainly regarding land uses and relating activities. This fact in its turn, leads to townscape pressures in certain areas, such as locations that can ensure an uninterrupted view to the caldera. In addition, due to the aforementioned peculiarities the candidate areas for construction and exploitation ought to fulfill the fundamental safety regulations against geodynamic processes and catastrophic phenomena, particularly landslides (Lekkas 1996).

The aim of this paper is to initially assess the Landslide Hazard that is not uniformly distributed along the length of the caldera slopes, and especially in some locations is small while in other locations medium or high, in relation to the existing conditions. An assessment of landslide risk follows with a three level calibration in order for the appropriated technical interventions to be launched and minimize the consequences.

2 LANDSLIDE HAZARD ASSESSMENT

The Landslide Hazard Assessment was based on the following factors, related to the manifestation of the phenomenon:

- The morphological conditions that although characterized by large morphological dip values throughout the caldera they vary from location to location and exhibit special characteristics and peculiarities. In addition, the geomorphological discontinuities recorded in several locations are significant.
- The variable geological structure throughout the caldera of the volcano. As it is known, the structure varies due to the composite nature of the volcanic complex with the presence of many volcanic centers that produced a variety of formations

that lie under the Upper Pumice Formation deposited during the last paroxysmal eruption and triggered the caldera formation.
- The existing geotechnical – technical – geological conditions that are primarily assigned by the lithological composition of the geological formations and as a result they vary significantly from location to location and secondarily assigned by the tectonic strain and the processes of erosion and weathering.
- The human interventions that play a determinant role – most of the times a negative one – which are represented mainly by additional load on the slopes, excavations, caverns, material disposals, creation of artificial debris fans etc.

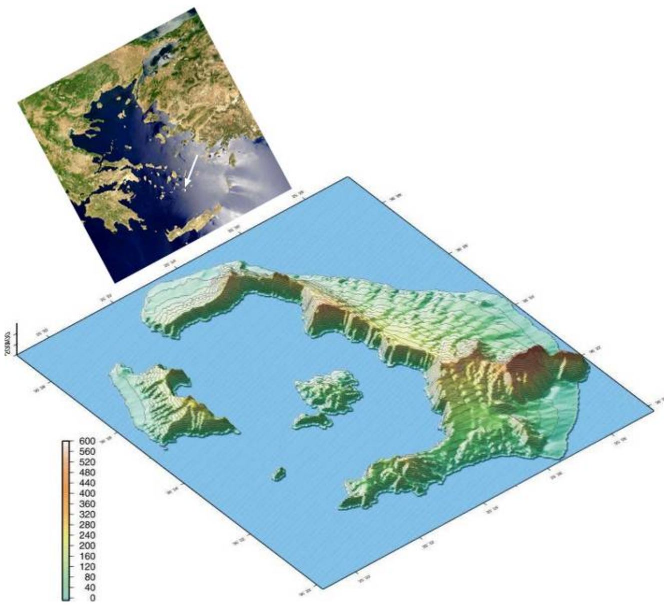


Figure 1. 3-D representation of the volcanic complex of Santorini (Thera)

3 ANALYSIS OF FACTORS AFFECTING THE LANDSLIDE HAZARD

As it was mentioned in the previous paragraph, in order to estimate the landslide hazard assessment the following factors were taken into account for the determination of hazard level in certain sectors of the Santorini volcano caldera.

3.1 *Geomorphological regime*

The Santorini Island complex includes the islands of Thera, Therasia, Nea Kammeni, Palea Kammeni and Aspronisi. These islands form an almost circular complex. The largest island, that of Thera, is semicircular, concave towards the west while Therasia and Aspronisi occupy the western part of the complex. All these islands represent the remains of the volcanic cone that collapsed and formed a ring around the gigantic submarine caldera.

The collapse of the volcanic cone and the caldera formation correspond to the catastrophic “pumice eruption” of the Minoan times (around 1.644 BC). The Nea and Palea Kammeni are islets located in the centre of the aforementioned ring and were formed gradually through lava flow activity postdating the catastrophic activity of the Minoan times.

The major diameter of the caldera in a N-S direction is approximately 11 km while the minor diameter in a E-W direction is approximately 7 km. The maximum caldera depth below sea level reaches 380m. The maximum caldera wall height above sea level reaches 300 m. The highest elevation (564m) is recorded on Thera Island at Profitis Ilias Mt., located to the northeastern part of the island (Figs 1-2).

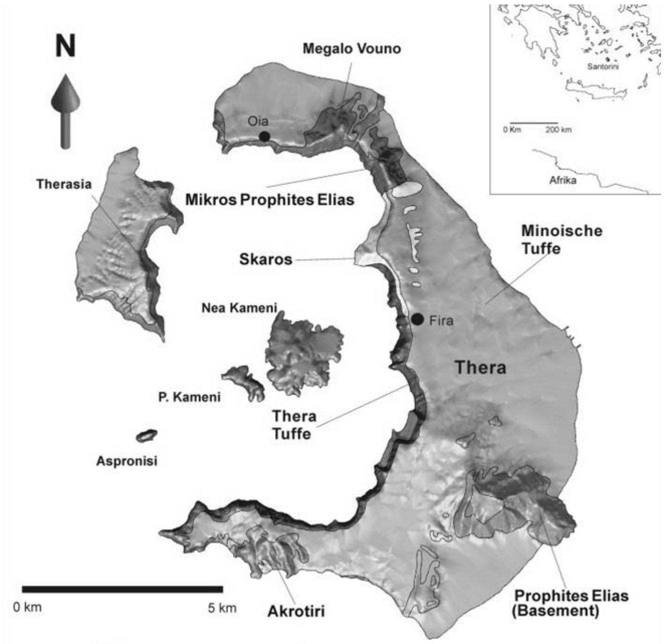


Figure 2. 3-D model of the island complex of Santorini with the main geological formations (Spyridonos et al., 1999).

The morphology of the island complex is composed by: (i) the internal rocky and steep slopes of Thera, Therasia and Aspronisi islands (Figs 3-5) forming the aforementioned caldera ring, characterized by high morphological dip values that in locations approach vertical values, with impressive morphological discontinuities and (ii) the external sections of the islands, characterized by smooth surfaces of relatively low dipping angles and radial distribution to the volcanic centre, representing the remnant outer slopes of the volcanic cone.

The morphological discontinuities and the morphological dips play an important role in landslide rock-fall occurrence and determine in a great extent the landslide hazard.

Figure 3. View of the volcanic complex of Santorini (Thera) including the Fira town on the caldera brow.

Figure 4. View of constructions founded on lava in the area of Skaros at the caldera brow in critical stability conditions.

Figure 5. View of Fira town from the north. High morphological dip values and morphological discontinuities can be observed.

3.2 *Geology*

A variety of geological formations can be observed in the geological structure of the Santorini volcanic island complex including basalts, andesitic basalts, andesites, dacites, rhyodacites, rhyoliths, pumice, ignimbrites etc., (Druitt et al. 1999, Druitt et al. 1989, Fouque 1879, Friedrich 2000, Heiken & McCoy 1984, Lekkas 1999, Papastamatiou 1958, Pichler & Friedrich 1981).

The volcanic formations are the products of sequential volcanic activity during the Pliocene – Holocene (Figs 2-6). This activity was distributed in various volcanic centers that erupted in various volcanic periods and covered the Alpine substratum composed of metamorphic rocks mainly marbles and phyllites (Papastamatiou 1958), that outcrop in several locations around the caldera, the largest outcrop being that of Athinios port.

Figure 6. View of the caldera exhibiting sequential volcanic formations including the Upper Pumice formation as the topmost formation that was deposited during the Minoan eruption (~ 1644 BC.).

The geological formations represent a complex frame with sequences of volcanic formations that vary from location to location. In addition in several areas these formations are faulted by faults and fault zones distributed radial to the volcanic cone increasing the complexity of the volcanic structure.

Summarizing, the geological structure of the of the Santorini volcano island complex is very complicated both in a horizontal and in a vertical sense and as a result the landslide hazard varies considerably throughout the caldera slopes.

3.3 *Geotechnical conditions*

The geotechnical conditions along the slopes of the caldera of Santorini volcano, present a variety depending on the existent lithostratigraphic composition, structural deformation and weathering.

Essentially, along the slopes of the caldera, rocky formations outcrop exhibiting high standard values of geotechnical parameters that correspond to andesitic and dacitic lava while ground formations exhibit very poor values of geotechnical parameters corresponding to pyroclastic formations.

A primary factor controlling instability is the succession of the volcanic formation such as for example the presence of friable formations e.g. pyroclastics and pumice under the rocky lava formations. The weathering and erosion of these underlying formations leads to instability of the overlying lava formations resulting to increase of landslide hazard (Figs 7-8).

Figure 7. Views of the Pyroclastic Formations that compose the lower section of the slopes under Fira town. The discontinuities that develop in the overlying lava formations (arrows) that increase landslide hazard can be observed.

Figure 8. View of residential constructions founded on the brow of the caldera on lava formations.

In addition, in some locations, discontinuities observed in lava are expanding due to atmospheric processes or due to human activity and as a result large blocks become detached and slide. Finally, in many locations unconsolidated colluvial deposits have been recorded that form debris fans sliding down-slope (Figs 9-10).

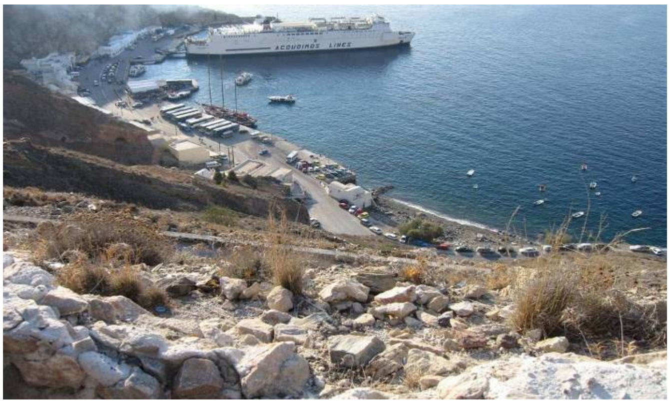


Figure 9. Unconsolidated colluvial deposits on the slopes of Athinios port.

Figure 10. View of colluvial deposits that develop on the caldera slopes near the cableway and Fira Port.

3.4 *Human activity*

Human presence is represented by urban – semi urban areas including all sorts of uses, intense touristic development and related activities, infrastructure works, quarry and mining constructions and finally cultural monuments.

Due to the comparative advantages of certain areas of the caldera, significant pressure for "exploitation" of land is exceeded, that most of the time leads to considerable alterations of the caldera features such as excavations, landscaping, constructions and additional load due to aggregate disposals etc. (Fig. 11).

Summarizing, human interventions in some cases have a negative effect on the stability of the caldera slopes.

Figure 11. a. Views of Oia, town located over Ammoudi cove. b. Constructions on Upper Pumice slopes with high morphological dip values. The existing stability conditions are aggravated by the numerous caverns located under the constructions (arrows).

4 LANSLIDE HAZARD SECTORS DETERMINATION

The Landslide Hazard sectors determination is an essential step towards the confrontation of the problem since it represents a useful tool that encloses and evaluates certain key factors necessary for the hazard assessment that in its turn is calibrated in three levels, Low, Medium and High (Fig. 12).

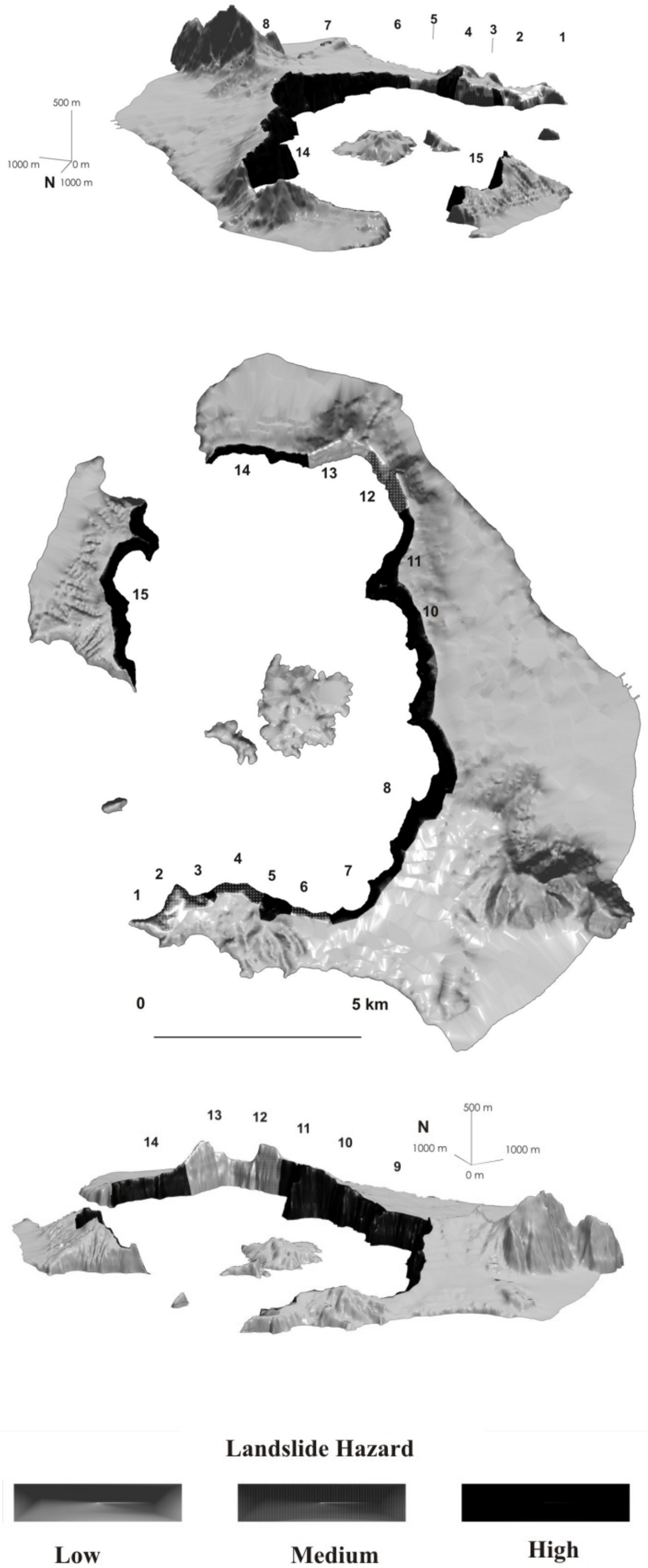


Figure 12. Sectors of Landslide Hazard on the caldera slopes of Santorini volcano.

In total, along the caldera slopes of Santorini volcano 15 sectors of Landslide Hazard were identified (Table 1).

Table 1: Landslide Hazard

SECTOR	1	2	3	4	5
1. Faros, Akrotiri	A	A	A	A	Low
2. Cape Aspronisi	B	A	A	B	Medium

3. Kokkinopetra	C	C	C	A	High
4. Theoskepasti	A	A	B	B	Medium
5. Akrotiri	C	C	C	A	High
6. Agios Georgios	A	B	B	A	Medium
7. Mpalos Cove	C	C	C	B	High
8. Athinios Cove	C	C	C	C	High +
9. Cape Alonaki	B	B	C	C	High
10. Fira					
a. Fira port	C	C	C	C	High +
b. Zones of medium morphological dip values	B	C	C	C	High
c. Slopes with high morphological dip values and discontinuities	C	C	C	C	High +
11. Cape Skaros	C	C	B	B	High
12. Mikros Profitis Ilias	B	B	A	A	Medium
13. Megalo Vouno	C	A	A	A	Low
14. Oia					
a. Ammoudi Cove	C	C	C	C	High +
b. Armeni Cove	C	C	C	C	High +
c. Zones of medium morphological dip values and caverns	B	B	C	C	High
d. Zones of high morphological dip values on slopes of upper pumice	C	B	B	C	High
e. Upper pumice – upper lava slopes with high morphological dip values and discontinuities	C	C	C	C	High +
f. Lava slopes	C	C	C	C	High +
15. Therasia	C	C	C	B	High

1: Morphology
2: Geological structure
3: Geotechnical conditions
4: Human interventions - activity
5: Landslide hazard

A: Positive
B: Borderline
C: Negative

5 LANSLIDE RISK ASSESSMENT

Based on the data collected and especially based on prominent sectors and the level of Landslide Hazard characterizing each sector, the Landslide Risk can be estimated.

At this point it should be mentioned that the Landslide risk is the measure of Landslide Hazard that is applied on works, constructions, humans that occupy each sector along the caldera (Table 2). In other words it is a measure of the possible or expected consequences – losses caused in the event of a landslide in each sector (Figs 13-14).

Table 2: Landslide Risk

SECTOR	1	2	3	4
1. Faros Akrotiri	Low	-	Low	-
2. Cape Aspronisi	Medium	-	Low	-
3. Kokkinopetra	High	-	Low	-
4. Theoskepasti	Medium	+	Medium	a
5. Akrotiri	High	-	Low	-
6. Agios Georgios	Medium	++	Medium	b
7. Balos Cove	High	-	Low	-
8. Athinios Cove	High +	+++	High +	b, c, d
9. Cape Alonaki	High	++	High –	b
			Towards N Low	
10. Fira				
a. Fira port	High +	+++	High +	b, c, d
b. Zones of medium morphological dip values	High	+++	High +	b, c
c. Slopes with high morphological dip values and discontinuities	High +	+++	High +	b, c, d
11. Cape Skaros	High	-	N section Low – S section High	b, c, d
12. Mikros Profitis Ilias	Medium	-	Low	-
13. Megalo Vouno	Low	-	Low	-
14. Oia				
a. Ammoudi Cove	High +	++	High +	b, c, d
b. Armeni Cove	High+	+++	High +	b, c, d
c. Zones of medium morphological dip values and caverns	High	+	High	b
d. Zones of high morphological dip values on slopes of upper pumice	High	++	High	b
e. Slopes of upper pumice – upper lava with high morphological dip values and discontinuities.	High +	++	High +	b
f. Lava slopes	High +	++	High +	b, c, d
15. Therasia	High	+	High	b, c, d

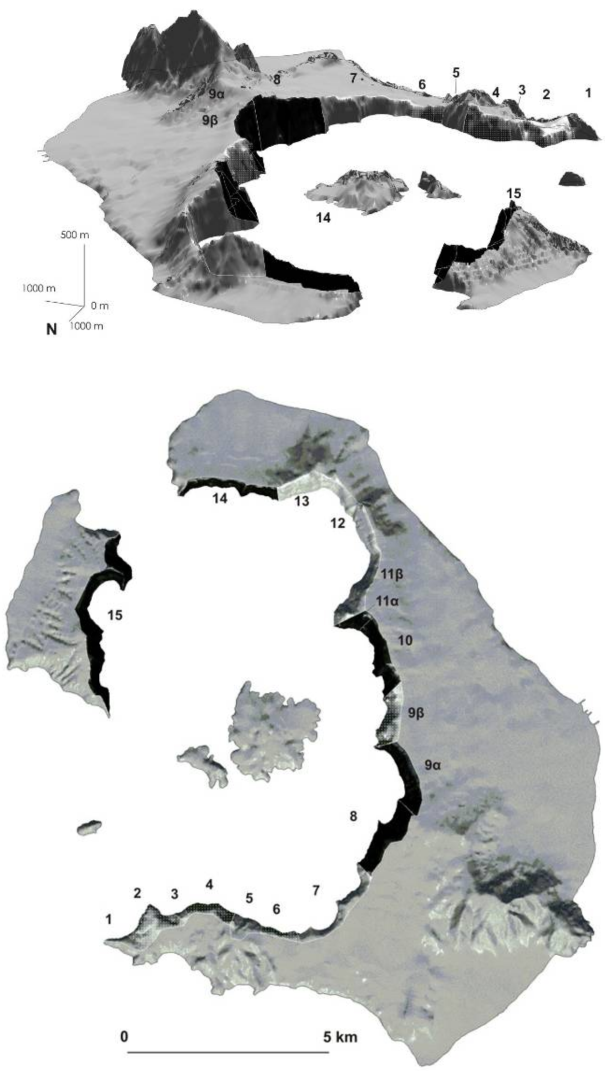
a: Interventions not needed
b: Supports – anti-erosion works
c: Restraint – trapping networks
d: Lashings

Figure 13. View of Fira town where landslide risk is considered as high due to the existing port constructions, the cableway and the large number of visitors during the summer period.

Landslide Risk, as in Landslide Hazard, is calibrated in three levels as Low, Medium and High and can be specialized or vary within each sector of Landslide Hazard depending on the existing infrastructure, activities and human presence (Fig. 15).

Summarizing, the Landslide Risk Assessment along the slopes of the Santorini volcano represents a useful guide for prioritizing interventions in order to construct works that will ensure maximum efficiency and significantly protect people and all sorts of infrastructure works and constructions.

Figure 14. View of Oia town for which landslide risk is considered as high.



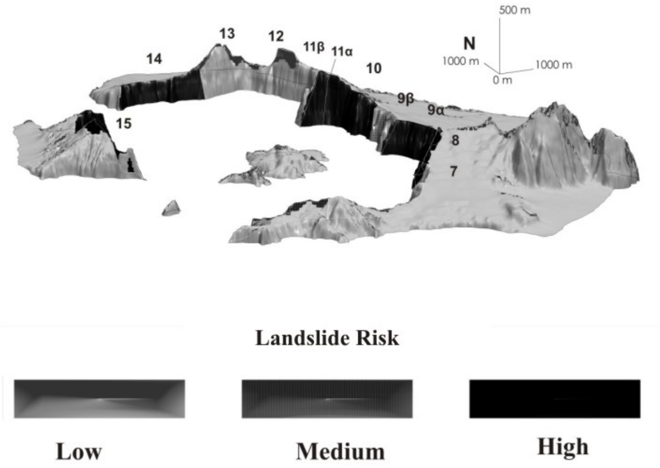


Figure 15. Sectors of Landslide Risk for the caldera of the Santorini volcanic complex.

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