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Urban and land planning of settlements in geodynamically hazardous regions of particular cultural, environmental and natural significance. The case of Oia-Santorini, Greece

E. Lekkas, D. Papanikolaou, P. Nomikou & M. Papanikolaou
Sector of Dynamic Tectonic Applied Geology, Department of Geology and Geoenvironment National and Kapodistrian University of Athens, Greece

ABSTRACT: The urban area of the historical municipality of Oia comprises a special environmental unit which combines historical buildings, a characteristic cycladic architecture as well as an impressive geomorphology and geological structure. Because of these features, the municipality of Oia has become a very popular tourist destination and as a result, suitable land use planning for expanding urban development is more than necessary. In this study, we evaluate the geomorphological, geological and geotechnical features of the complex-built area towards the inner side of the caldera, we suggest a microzonation map, and we assess the land use and urbanization suitability.

1 GENERAL

The area of the municipality of Oia and the entire island complex of Santorini (Fig. 1) is an exceptional for worldwide standards region, since it combines elements such as: a) The impressive geological—geodynamic activity and the geological structure and evolution of the volcanic complex. b) The geomorphological characteristics including the evolution of one of the largest calderas and one of the most impressive volcanoes worldwide. c) The strong historical heritage, including events and works directly related to the volcanic activity since prehistorical times and d) The characteristic architecture that occupies a large part of the built environment. These elements compose a special environmental unit, of exquisite beauty, characterized by its uniqueness and therefore this unit is presented as an international center of geocultural value. However, the aforementioned characteristics of the region trigger increased tourist flow which as a matter-of-course demands further "development" mainly in terms of land planning and use. Even more so, urban planning demands become higher for some specific areas benefited by such special parameters as the panoramic view to the caldera. However, while planning, especially that of certain areas, may at times implicate violation and distortion of the physicogeographical-environmental character of the region, it also ought to be secure against disastrous geodynamic phenomena. Thus, the aim of this research is to determine in geological, geotechnical and geoenvironmental terms the suitability of urban use and development in certain parts of the Oia settlement.

2 DESCRIPTION OF THE REGION

The island complex of Santorini, includes the islands of Thera, Therasia, Nea Kammeni, Palaia Kammeni and Aspronisi (Fig. 1), arranged in a circular shape. The largest island, Thera, is semicircular and its concave side is looking to the west, while Therasia and Aspronisi lie at the western part of the complex. They all represent the remains of the collapsed volcanic shield and form a ring around the gigantic submarine caldera that was formed around 1600BC (Heiken & Mc Coy 1984, Pyle 1989, Friedrich 2000). The Nea and Palaia Kammeni

Figure 1. Topographic map of the island complex of the Santorini volcano. The arrow indicates the location of the Oia settlement.

are islets located in the center of the caldera and formed by the accumulation of successive lava flows, following the disastrous activity of 1600BC. (Fouque 1879, Washington 1926, Ktenas 1927, Liatsikas 1942, Georgalas 1953).

The maximum diameter of the caldera is N-S trending nearly 11 km long, while the minimum diameter is E-W trending approximately 7 km long. The deepest point of the caldera bottom morphology reaches 380 m below sea level, while the caldera walls are approximately 300 m high. The Oia settlement, a traditional and protected settlement, is located at the northern end and at the highest section of the volcano caldera.

3 GEOMORPHOLOGICAL ANALYSIS OF THE OIA REGION

The research was originally implemented with morphological analysis under a scale of 1:1000, based on the values and directions of the morphological slopes. The morphological analysis showed that the greater region of Oia comprises three geomorphological units (Table 1, Fig. 2).

Among the three morphological units, units B and C draw scientific interest because their characteristics determine in a great extent the land use and the urbanization suitability at this vulnerable area which extends to the inner side of the caldera. Morphological Unit A, raises no suitability issues because of its favourable morphological conditions.

4 GEOLOGICAL STRUCTURE AND GEOTECHNICAL CONDITIONS OF THE STUDY AREA

Detailed geological investigations and mapping (scale 1:1000) combined with previous research (Fouque 1879, Pichler et al. 1980, Druitt et al. 1999) resulted in the map of Fig. 3. The geological formations from (younger to earlier) top to base are as follows:

SCREE FORMATION. It consists of unconsolidated scoriae, lava and pumice fragments of variable sizes and up to a few hundreds of cubic meters, which often slide on the steep caldera slopes forming impressive fans. This formation increases the risk of landslide-rock failure hazard in the Ammoudi and Armeni settlements.

UPPER PUMICE FORMATION. It consists of coarse-grained to fine-grained rhyodacitic pumice, at least 30 m thick, deposited upon the upper layer of the Upper Lava Formation and is dipping 5–10° to the NNW. Pumice is known for its good geotechnical characteristics

Table 1. Distinction among the three morphological units of the Oia region.

Morphological unit	Morphological dip	Geographic boundaries
A	30% to the north	To the south: between the volcanic cone and the caldera To the north: by the coastline It covers the largest part of the study area extending to the north of the caldera watershed (outer side or the volvanic cone)
B The most densely constructed part of Oia settlement	Section 1: to the south of the watershed, less than 30% dip, built mostly for public use (roads, squares etc) Section 2: at lower altimetry, 30–45% dip, private properties 45–60% dip develops at locations where morphological discontinuities occur The 2 sections are E-W trending	To the south: by the morphological discontinuities of the caldera cliffs To the north: by the caldera watershed Fig. 5
C	More than 45% and at locations approaches perpendicular gradients	Steep area below the Oia settlement, the cliffs of Lava and Scoriae formations

which has in the past rendered it suitable as a foundation ground for the construction of some uniquely made basements-semibasements, the so called 'iposkafa'. The good geotechnical behaviour of pumice is evidenced by the stability and good preservation of the slopes in spite of their high (almost perpendicular) gradient. It has a permeability coefficient (k) that varies from 4.0×10^{-1} to 0.8×10^{-5} cm/sec, high erodability, indicative ground tension 1.5 kg/cm for foundation depth that exceeds 2 m^2. Furthermore, the unit weight is $\gamma = 10$ KN/m^3, while the Young deformation modulus possesses values from 20.5 to 550 MPα (average value 320 MPα) and the uniaxial compressive strength varies from 0.1 to 4.0 MPα. In specific, the uniaxial compression tests record small values towards the lower section of the Morphological Unit B. At last, the rock mass is not divided by sets of joints that could control its relaxation.

UPPER LAVA FORMATION. It is composed of quartzitic-andesitic lavas with few intercalations of scoriae and pyroclastic materials, in sequential horizons of average dip 5–10° towards the NNW. This formation has variable geotechnical characteristics due to its heterogeneity (e.g. lava, scoriae, pyroclasts). In practice, up to four main horizons can be distinguished each for the lava, scoriae and pyroclastic horizons. The thickness and number of the intercalated horizons increases gradually from west to east. In general, the lava formation is a rocky formation with exceptional geotechnical behavior. Its horizons vary from 5 to 8 m thick and at some locations fractures arising from the fast cooling of the rock are present. The fractured surfaces in combination with the thickness of the upper horizon form blocks that have a volume of approximately 125 m^3 and have become unstable after the construction of basements and seismic activity, and are thus very prone to landslides.

SCORIAE FORMATION. It is composed of quartzite-andesitic scoriae with layers of maroon to black colored lava fragments. It is an heterogeneous formation, resembling an agglomerate, comprising horizons of scoriae and lava fragments that usually range from 5 to 30 cm and rarely exceed 80 cm. The formation is in total around 40 m thick, dipping 5–10° towards the NNW. The morphological dips in the area exceed 100% and where the agglomerate is poorly consolidated it is easily eroded and deposited in alluvial fans on the caldera slopes.

LOWER LAVA FORMATION. It comprises mostly intercalations of black and white quartzitic, latiandesitic lavas up to 5 m-thick each, while yellowish pumice horizons, 7 m-thick,

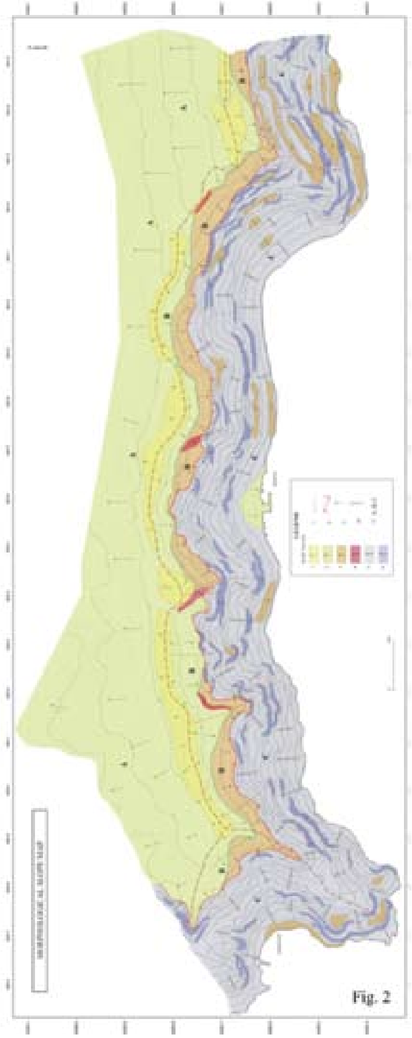

Figure 2. Morphological map of the greater region of Oia. 1. 0–5%, 2. 5–30%, 3. 30–45%, 4. 45–60%, 5. 60–120%, 6. >120%, 7. watershed, 8. Morphological discontinuity, 9. Dip direction 0–45%, 10. Dip direction >45%, 11. Morphological units.

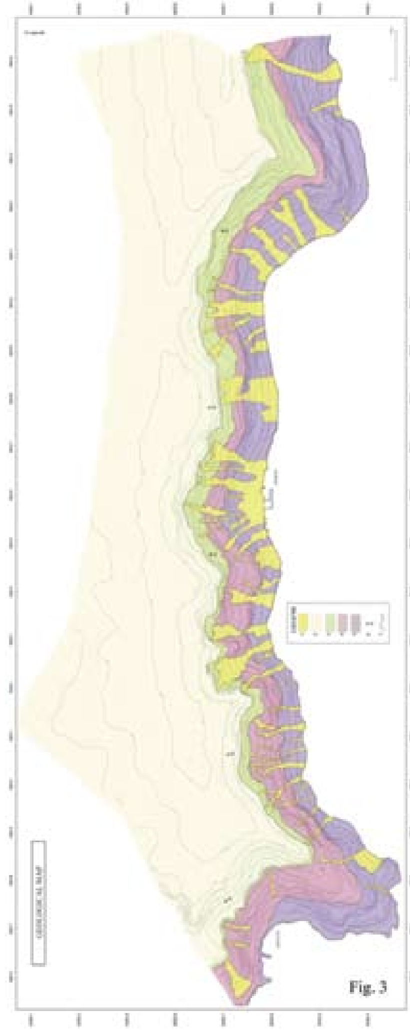

Figure 3. Geological map of the greater study area. 1. Scree formation, 2. Upper Pumice formation, 3. Upper Lava formation, 4. Scoriae formation, 5. Lower Lava formation, 6. Dip direction (5–10%), 7. Boundaries of formations.

are rarely observed. The maximum visible thickness of the formation is estimated to 60 m and the general dip of the bedding is 5–10° to the NNW.

Besides the side scree formations being highly unfavorable for the safety of the Ammoudi and Armeni settlements, dominant role to the stability configuration at the inner caldera borders of the residential area play the Upper Lava and Upper Pumice formations. This will hereafter be presented with the description of key-locations and case studies.

5 PRESENTATION OF REPRESENTABLE STUDY CASES

In the following paragraphs we present a few representative study cases along the caldera rim in an attempt to evaluate the stability of the greater area of Oia.

5.1 *Study case A: Armeni and Ammoudi bays —steep slopes*

Armeni and Ammoudi bays, south and west of the Oia settlement respectively, are limited areas where few scattered constructions and small marine works occur. The steep overlying cliffs and slopes comprise mostly the Lower Lava and Scoriae formations at the lower part, and the Upper Lava and Upper Pumice formations at the upper part, while at places impressive alluvial fans have formed (Figs. 4, 5). The Scoriae Formation, comprising the largest part of the lower cliffs behind the two bay settlements, is a relatively loose and highly erodible material and therefore constitutes high risk for landslides and rockfalls with dramatic consequences to the settlements. Recent rockfall events, with blocks size reaching few hundred cubic meters, can be seen and are often triggered either independently or by a volcanic or earthquake event such as that of 1956. The current supporting walls and walls for trapping rock blocks can be effective only for small-scale phenomena and any further reinforcement of the walls would never adequately protect the settlements.

5.2 *Study case B: Zones of gentle morphological dip in the upper pumice slopes*

The areas of the Morphological Unit A and the upper section of the Morphological Unit B do not exceed 30% of morphological dip resulting in good stability conditions. Additionally, the sufficient thickness (at places reaching 30 m) and the good geotechnical characteristics of the Upper Pumice Formation along with the scarcity of basements at those locations lead to surface constructions that do not present failures. These areas are considered suitable for settlement development.

5.3 *Case study C: Zones of moderate morphological dip—basements 'iposkafa'*

Several basements 'iposkafa' have been constructed, quite a long time ago, on the Upper Pumice Formation. These basements have been the typical houses in Santorini because their excavation was highly favored in the pumice, a material known for its good geotechnical properties. At locations with favorable morphological dips, that is between 30 and 45%, the basements increase in numbers and form unique settlements which as part of the traditional and historical urban web of the region need to be protected by forbidding further construction activities. In particular, foundations over or next to the basements should be avoided so as to prevent the occurrence of stability failures.

5.4 *Case study D: Zones of great morphological dip on upper pumice slopes*

Along the inner side of the caldera and above the Ammoudi bay area, the slopes of the Upper Pumice Formation have great morphological dips that exceed 45%. In specific, locations such as Goulas and above the Ammoudi bay where the slopes dip with greater than 45% are considered unsuitable for settlement development. It is worth noticing that during the earthquakes of 1956 the regular surface constructions in these specific zones were seriously damaged while the basements 'iposkafa' were almost unaffected (Papastamatiou & Voutetakis 1956). No further urban development should be conducted at the steep slopes (over 45%) under the physical caldera boundary since they represent the main stratigraphy of the volcanic complex evolution and a rare geotope.

5.5 *Case study E: Upper pumice and upper lava slopes with great morphological dip and discontinuities*

The large morphological dip (more than 45%) of the slopes below the physical boundary of the caldera are the result of erosion and corrosion of the Upper Lava Formation at the base and the Upper Pumice Formation at the top and in particular the differential erosion of the easily eroded intercalations of scoriae and pyroclastics. The instability of the pumice-lava

Figure 4. Views of Armeni bay. The dipping slopes with the morphological discontinuities, the impressive development of the scree fans and some minor extent intervention for landslides are notable. The settlement is characterized by high landslide risk that can be extended during seismic load.

Figure 5. Views of the Ammoudi bay and the settlement of Oia. The steep slopes that the Scoriae formation forms can be viewed. In addition the supporting walls for the protection of the settlement from minor rockfalls and scree are showed. The settlement is in high risk due to the rockfalls and landslides that in case of an earthquake they can be extended.

system is also affected by vertical discontinuities existing in the Lava Formation which weaken the support system and make it easily detached and ready to collapse. Such is the case witnessed along the road from Oia to Armeni, where lava blocks and overlying pumice are nearly detached.

5.6 *Case study F: Lava slopes*

Despite the good geotechnical properties of lava as a rock, a network of primary vertical discontinuities (at a spacing of 2–7 m) intersects the formation and in combination with the nearly horizontal 5 m-thick bedding rock blocks (average size of 125 cubic meters) are developed. On top of that, the underlying horizons of scoriae and pyroclastics are susceptible to erosion and cause the lava blocks to gradually lose their support and become easily detached. Such is the case of the construction areas along the road from Oia to Armeni.

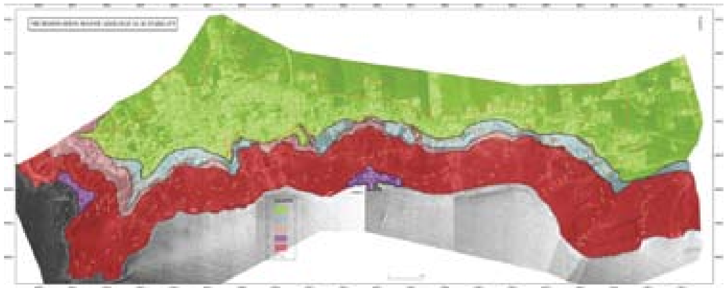

Figure 6. Microzonation map of geological suitability for the region of the Oia settlement. 1. Geologically suitable areas for urban development and constructions, 2. Geologically suitable areas for urban development and constructions under certain conditions, 3. Geologically unsuitable areas for urban development and constructions. Only the conservation and restoration of existing constructions and basements, 4. Geologically unsuitable areas for urban development and constructions. Restoration and conservation of existing constructions is allowed (Armeni & Ammoudi settlements), 5. Geologically unsuitable areas for urban development and constructions, 6. Boundary of settlement.

6 CONCLUSIONS

In order to evaluate the hazard and demarcate the region into groups and risk zones according to the level of stability, the following factors were taken into account.

- The morphological dip and discontinuities.
- The succession of geological formations, and the structure of the Upper Lava and Upper Pumice formations particularly.
- The presence and structure of discontinuities in the Upper Lava Formation.
- The spatial variation of geotechnical conditions.
- The interventions in the natural environment (e.g. altering the morphology and excavating the 'iposkafa' basements).

On the basis of the aforementioned factors and data collected from the greater region of Oia, microzones of special stability conditions can be distinguished as follows (Fig. 6).

6.1 *Geologically suitable areas for urban development and constructions*

This microzone refers to areas of the Morphological Unit A and to the first section of the Morphological Unit B south of the watershed with less than 30% of morphological dip. These areas occur exclusively in the Upper Pumice Formation, which is at least t 20 m thick, and its good geotechnical properties render it suitable for constructions.

6.2 *Geologically suitable areas for urban development and constructions under certain conditions*

It refers to the second section of the Morphological Unit B. The larger part of the settlement of Oia is built in this microzone which is mostly developed in the Upper Pumice Formation characterized by moderate values of morphological dip, relatively lower geotechnical pumice values, localized phenomena of surface erosion and high presence of ′iposkafa′ basements. These sections are considered geologically suitable for urban development and construction under the following conditions:

- Exercise extra caution in the foundation and surrounding areas for the detection of basements that could affect the constructions stability.
- Investigation of the geotechnical properties of the ground foundation and construction of terraces at the slopes in order to prevent localized landslides.

- Where stability failures are detected thorough geotechnical investigation should be carried out for the foundation and surrounding areas.

6.3 *Geologically unsuitable areas for urban development and constructions. The conservation and restoration of extisting constructions and basements is suggested for the stability of the slopes and the safety of the overlying constructions*

This microzone comprises areas of large morphological dip occurring mostly in the Upper Pumice Formation where a great number of basements has been constructed. Because the traditional settlement of 'iposkafa' basements and the physicogeographical environment should be preserved and the stability of overlying and adjacent constructions should be ensured, restoration, reinforcement and conservation of the existing constructions supporting walls and basements should be assured.

6.4 *Geologically unsuitable areas for urban development and construction. Restoration and conservation of existing constructions is allowed (Armeni & Ammoudi settlements)*

This zone comprises mainly the areas of Ammoudi and Armeni, which run a high risk of landslides and rockfalls particularly during an earthquake or seismic activity related to volcanic activity. For these regions particularly, it is suggested that the reconstruction, conservation and restoration of the already existing constructions be allowed.

6.5 *Geologically unsuitable areas for urban development and constructions*

This microzone comprises areas of the Morphological Unit C that is characterized by great morphological dip values (more than 45%) corresponding to the slopes and cliffs of the caldera. It also refers to the slopes of the Upper Lava Formation which due to the differential erosion of the underlying beds of the Scoriae Formation comprise a high risk of rock falls and landslides. Moreover, the foundation over the top horizons of the Upper Lava Formation which is also bearing discontinuities is prone to failures in the support system of constructions.

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