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## Palaeoliquefaction phenomena and liquefaction hazard map at Zakynthos island, W.Greece

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**ABSTRACT:** Historical descriptions of two liquefaction phenomena caused by the earthquakes of 1809 and 1840 at Zakynthos Island are given, following detailed search on relevant historical sources. The verification of liquefaction is based on field investigation and geologic survey. Basic geotechnical conditions are then specified at critical areas where the results of the first stage geologic survey were promising. The synthesis of the incoming data made clear that during the earthquakes of 1809 and 1840 liquefaction took place at Episkopiani and Keri, respectively. Areas of not historically proven liquefaction, during the earthquake of 1840, and areas prone to future liquefaction, are also specified (Alikes, Laganas, Zakynthos City). As a conclusion, historical sources seem to be a very useful guide in the attempt to recognise potential hazards and reduce seismic risk.

**RÉSUMÉ:** Des descriptions historiques sont données après l'étude détaillée des sources historiques de deux phénomènes de liquéfaction pendant les tremblements de terre de 1809 et 1840 de Zakynthos. La vérification des phénomènes est basé sur les observations et l'étude géologique du terrain. Les conditions géotechniques fondamentales sont spécifiées aux régions critiques, où les premiers résultats de l'étude géologique étaient prometteurs. La synthèse des données a montré que pendant les tremblements de terre de 1809 et 1840, des phénomènes de liquéfaction ont eu lieu à Episkopiani et Keri, respectivement. En plus, des régions qui sont vulnérables à liquéfaction future (et qui n'ont pas subi des telles phénomènes pendant le tremblement de terre de 1840) ont été spécifiées (Alikes, Laganas, Cité de Zakynthos). Pour conclure, on peut dire que les sources historiques constituent un guide très pratique pour évaluer les hasards possibles et réduire les risques sismiques.

### 1 INTRODUCTION

Zakynthos Island is located at Western Greece in a region characterised by high seismicity due to the convergence of the European and the African tectonic plates (Fig. 1). Devastating earthquakes have repeatedly ruined to the ground Zakynthos City, causing numerous deaths. The last devastating earthquake (1953) and the following fire caused severe damages to the build environment and some precious cultural monuments as the Public Library, where prototype and unique historical evidence were kept. Thus, study of historical seismicity, which could have provided a starting point for the identification of catastrophic geodynamic phenomena, was made extremely difficult. However, detailed examination of the remaining historical sources and archives revealed a few reports related to liquefaction at Zakynthos Island.

The scope of this study is to evaluate this information through geological - geotechnical investigation and to point out probable liquefaction zones. This is more important today since the island is under rapid development (hotels, roads, dwellings) and land use change.

### 2 HISTORICAL DATA

Two are the main earthquakes that were probably connected to liquefaction. Zois (1893) reported that during the earthquake of June 2nd 1809 a hole "two feet wide" was observed along the south bank of the river running through Episkopiani, a site at the south of Zakynthos city, and that "sulphur smell" gas was coming out of it. This is, as far it is known, an accurate description of common liquefaction surface effects, which were also observed during the

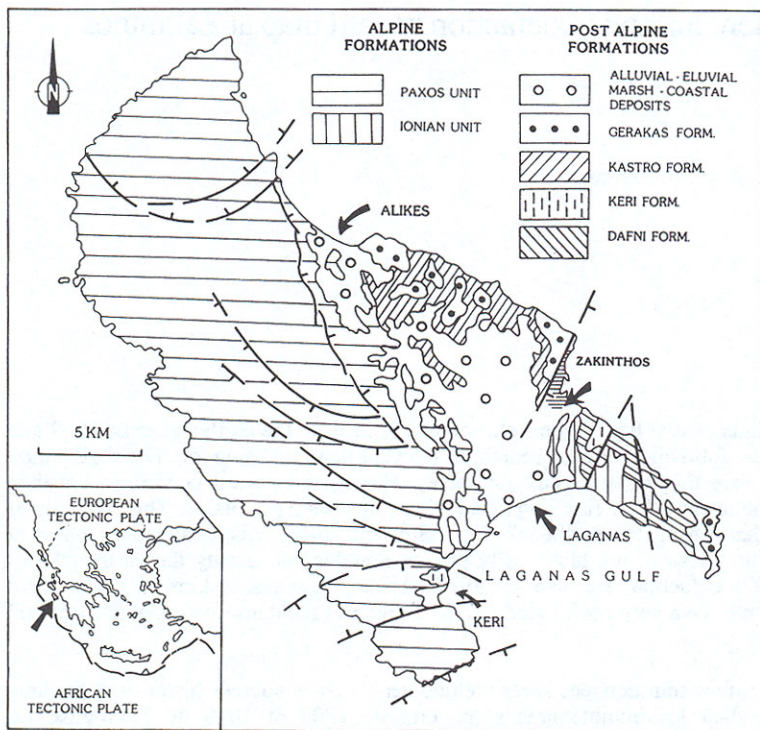


Figure 1. Geological sketch map of Zakynthos Island.

earthquakes of 1988 and 1993 within W. Greece mainland (Mariolakis et al. 1990, Lekkas 1994). Chiotis (1886) has reported, for the earthquake on 18/30th June 1840, "ground water emerging three feet above ground level", "sand coming out of trenches along Avyssos beach", "boiling bitumen". Zois (1893) reported that during the same earthquake "many wells, as well as the torrent, which runs along the east part of the town, flooded".

Both descriptions can be safely related to liquefaction phenomena. Chiotis' report corresponds to Keri area, whereas Zois' second report does not include geographical positioning of the liquefied zone.

### 3 GEOLOGICAL APPROACH

Evaluation of liquefaction potential using geological information was attempted not only for sites stated in historical reports but also for areas without any past liquefaction incidents.

Alpine Formations and Post Alpine Formations, which lie unconformably on the former (Fig. 1), essentially, form Zakynthos Island. Alpine

Formations belong to Ionian Unit and Paxos Unit which are two well-known geotectonic units (Horstman 1967, Bizon 1967, Sorel 1976, Dermitzakis 1978, Nikolaou 1986, Lekkas 1993). Ionian Unit, comprising Triassic evaporites, Mesozoic limestone and breccia, outcrops at south-east Zakynthos. Paxos Unit occurs at the west half of the island and is composed of calcareous formations at the bottom, and marl of Upper Cretaceous - Upper Miocene age at the top. The Alpine formations are not subject to liquefaction due to their good mechanical properties.

Post Alpine formations (Dermitzakis et al. 1977, Dermitzakis 1978, Nikolaou 1986, Lekkas 1993), are the following, in stratigraphic order:

Dafni Formation. Conglomerate, sandstone, marl and siltstone alternations with some gypsum intercalations (Middle - Upper Miocene). Thickness is more than 300 m.

Keri Formation. Apart from marly limestone the formation also involves Lower Pliocene marl. Overall thickness is a few tens of metres.

Castro Formation. It is a relatively thick formation (200 m) of Middle - Upper Pliocene age

composed of grey and blue clayey marl, clay, and sandstone.

Gerakas Formation. Pleistocene calcareous sandstone, 50 m thick, alternating with clay.

Alluvium. It is a thin (10 m overall thickness) formation, that covers the flat, low level region and is essentially composed of loose, fine particles with rare pebbles. Eluvial mantle due to weathering is less than 3 metres thick.

Coastal Formation. Loose materials of varying size found along the beach with thickness not greater than 5 metres.

Scree - Talus. Typical weathering products on steep slopes.

Marsh Deposits. They are observed at few sites along the coast and are composed of clay, silt, sand and peat up to 5 m thick.

Given that liquefaction takes place at loose sand and silt, alluvium, coastal formation and marsh deposits have high liquefaction potential. Areas prone to liquefaction can therefore be recognised. At the following sites liquefaction potential is greater due to special geologic conditions.

Keri Area. Coastal Deposits, Marsh Deposits and Alluvium (Fig. 2a) are exposed and are unconformably lying on Alpine Formations.

Groundwater table at the plane coastal section is on the surface and, in conjunction with the favourable geologic conditions present, can explain the liquefaction phenomena of 1840 (Chiotis 1886).

Alikes Area. The geology of this region involves Scree, Alluvium, Coastal Deposits, Gerakas Formation and Paxos Unit (Fig. 3a). At plane surfaces and at the coastal zone, where Alluvium, Marsh and Coastal Deposits dominate, watertable is 0.5-1.0 m deep and therefore liquefaction potential is high. However, presence of liquefaction incidents on 1840 is probable (Fig. 4).

Zakinthos City - Laganas Area. At this case Alluvium, Coastal Deposits and Marsh deposits are on top of Post Alpine Formations (Kastro, Dafni Formations) or Ionian Unit (Fig. 5a). At Zakynthos City and Laganas Bay coastal zone groundwater is less than 2 m deep and the geology favours liquefaction (Alluvium, Coastal Deposits, and Marsh Deposits). Thus, historical presumptions suggesting liquefaction at Episkopiani, located at the south edges of modern Zakynthos City, due to the 1809 earthquake are, most likely, true. Moreover, the geology of this particular area makes it a strong candidate for the liquefaction of 1840.

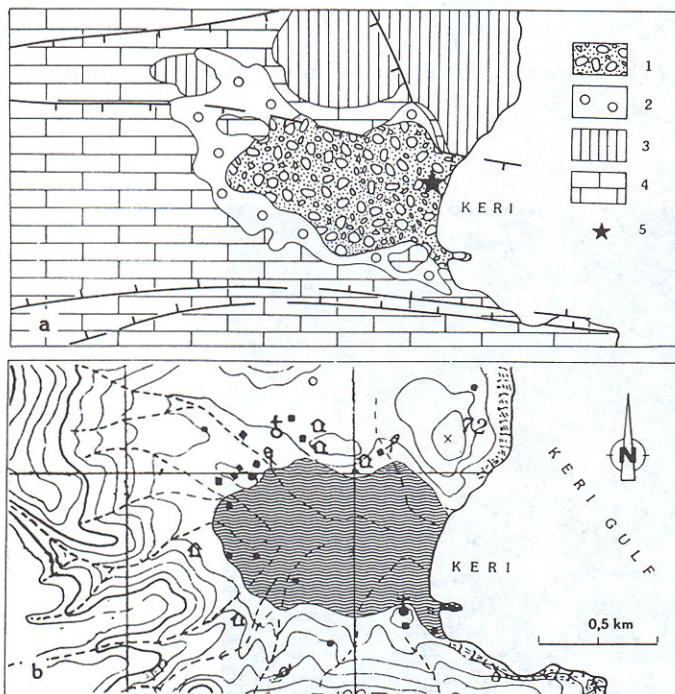


Figure 2a. Geological map of Keri area (1. Coastal and marshy deposits, 2. Alluvial, 3. Keri formations, 4. Alpine formations, 5. Liquefaction site, according to historical data, during the 1840 earthquake).

b. Liquefaction-prone area (dashed).

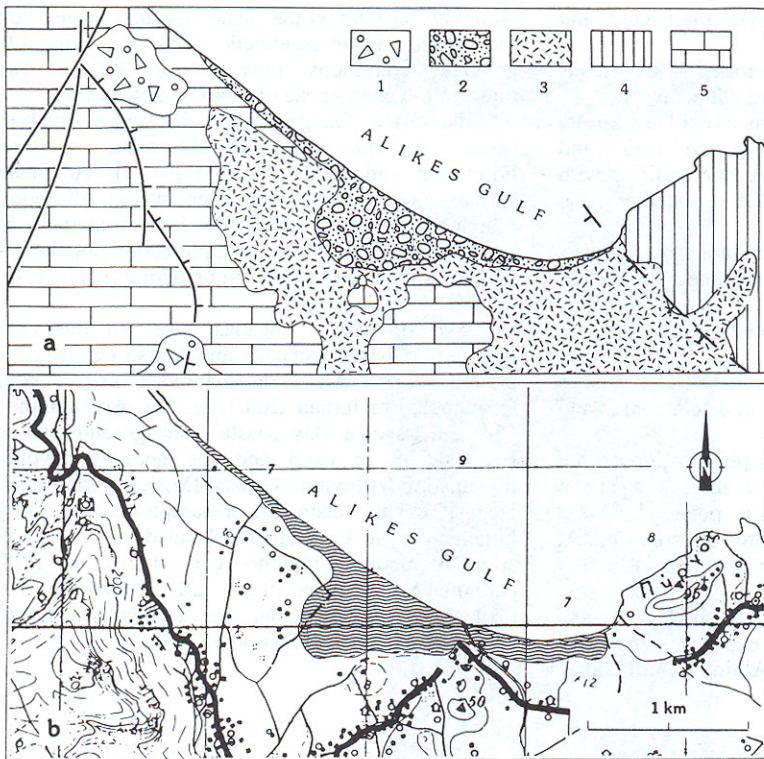


Figure 3a. Geological map of Alikes area (1. Talus Scree, 2. Coastal and marshy deposits, 3. Alluvial, 4. Gerakas formation, 5. Alpine formations).  
 b. Liquefaction-prone area (dashed).



Figure 4. General view of the liquefaction-prone sites at Alikes.

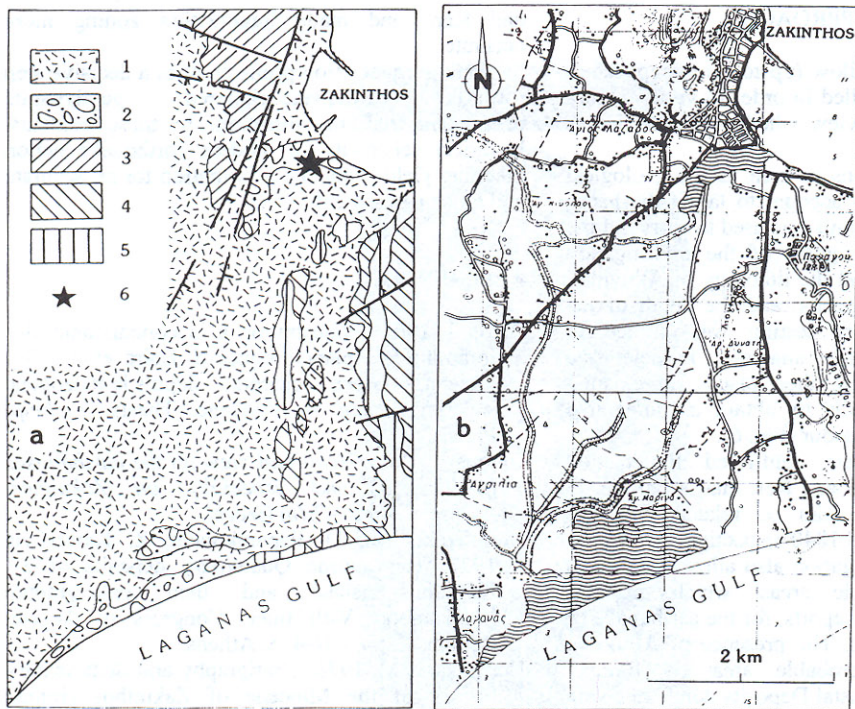


Figure 5a. Geological map of Zakynthos city - Laganas area (1. Alluvial - Eluvial, 2. Coastal - Marsh deposits, 3. Kastro formation, 4. Dafni formation, 5. Alpine formations, 6. Liquefaction site, according to historical data, during the 1809 earthquake).

b. Liquefaction-prone area (dashed).

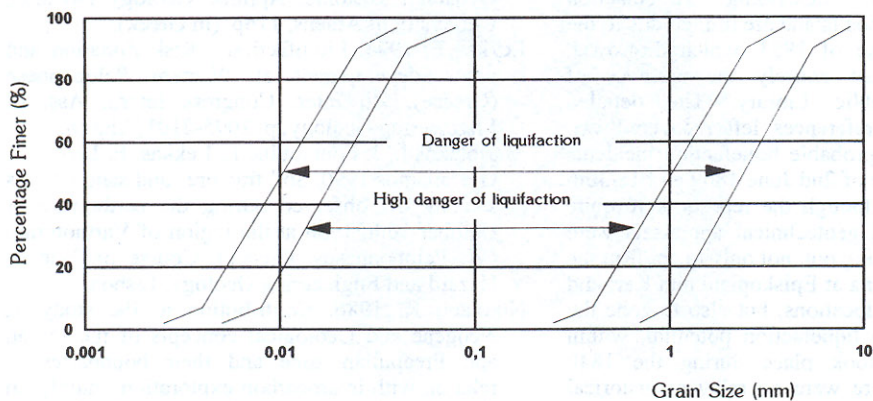


Figure 6. Diagram of grain size analysis from Keri and Episkopiani areas where liquefaction took place in 1840 and 1805, respectively.

#### 4 GEOTECHNICAL APPROACH

A large number of shallow (up to 8 m deep) hand-angled cores were drilled in order to verify from a geotechnical point of view whether liquefaction is possible or not.

Historical descriptions as well as the geological survey were taken into account to target the hand-angled cores. A small unit was used to carry out the drillings. The primary goals of the investigation were to identify in detail the lithology of Alluvium, Coastal and Marsh deposits, and the depth of the water table. Laboratory testing was limited in particle size distribution analyses. Particle size distribution curves were then placed on existing curves of liquefied soils to obtain an integrated picture of material behaviour (Fig. 6).

Geotechnical analysis confirmed liquefaction incidents at Episkopiani and Keri that, according to the historical sources, can be related with the earthquakes of 1809 and 1840 respectively.

Geotechnical investigation also allowed zonation of liquefaction-probable areas, which are not mentioned in historical reports, for the earthquake of 1840 (Figs. 2a, 3a, 5a). The presence of Alluvium within liquefaction probable areas is limited, whereas Marsh and Coastal Deposits dominate. Note that the same zone is prone to liquefaction phenomena during future earthquakes. With regard to alluvium, loose sand with silt intercalations was found to be more dangerous than other facies of "Alluvium".

#### 5 CONCLUSIONS

Historical sources describing liquefaction phenomena at Zakynthos Island are limited due to the devastating earthquake of 1953, which destroyed, among others, almost entirely the archives of Zakynthos City Public Library. The detailed examination of the references left recovered two reports with regards probable liquefaction incidents during the earthquake of 2nd June 1809 and 18/30th October 1840. Even though the reports were quite clear, geological and geotechnical appraisals were also carried out, pointing out, not only to confirm the liquefaction phenomena at Episkopiani and Keri and to identify the exact locations, but also to zone the area, with regards to liquefaction potential, within which liquefaction took place during the 1840 earthquake, since there were no relevant historical data.

Geological conditions favourable for liquefaction were found at Episkopiani and Keri and at: Alikes, Zakynthos City and Laganas, which were not known before. Geotechnical investigation strengthened the conception of liquefaction incidents at Episkopiani

and Keri, and made liquefaction zoning more accurate.

Zoning liquefaction prone areas is a decisive step towards earthquake-triggered geodynamic phenomena risk minimisation. In these contents, historical seismicity in modern earthquake action planning yields valuable information for an accurate and quick assessment.

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