Liquefaction-induced ground disruption triggered by the earthquake of June 8, 2008 in NW Peloponnesus, Greece

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Introduction
A strong earthquake occurred on the NW Peloponnesus on June 8, 2008 inducing several surface effects and structural damages in the broader epicentral area. The Ms 6.5 NW Peloponnesus earthquake, caused by a N20E to N30E (according to the available focal mechanisms) dextral strike slip fault, affected a large area from Kato Achaia to the north to Amaliada to the south. According to the National Observatory of Athens, Institute of Geodynamics (NOA), its focus was located at 37.98°N 21.51°E at depth 25 km while the event was located by the Seismological station of the Aristotle University of Thessaloniki at 37.944°N 21.544°E and 3 km depth.

The secondary effects triggered by the event were spread over a wide area at the NW Peloponnesus, though the most severe ones were reported in the direction of the fault. In particular, landslides were observed close to the epicenter at the village of Valmi while rock falls were observed at the villages of Santomeri and Portes, respectively, causing damages at roads and houses. Moreover, ground ruptures with local normal character and slight strike-slip component up to 20cm vertical and 15cm horizontal movement was observed close to the village of Nisi, causing damage to a bridge.

In this paper, the earthquake-induced liquefaction phenomena are presented while a map of the area was compiled showing their distribution. Moreover, published criteria regarding the occurrence of liquefaction manifestations such as historical seismicity of the area and the epicentral distances of the sites are examined. Finally, the grading characteristics of the sandy material that was ejected from ground fissures are presented and compared to the boundary curves proposed by Tsuchida (1971) regarding the possibility of liquefaction.

Geology of the area
Most part of the NW Peloponnesus is covered by a thick (>1km) sequence of Neogene – Quaternary sediments. These formations of Pliocene – Pleistocene age, consist of sands, shales, clays, marls, limestones and conglomerates, deposited in shallow marine/littoral and lacustrine conditions (Hageman, 1976; Tsolfias, 1977,1980, Fleury et al., 1981). The area around Lake Pinias is covered by sediments of Valmi Formation, consisting of intercalations of brown and green clays, white to yellow sands and silts, and conglomerates (Fleury et al., 1981; Stamatopoulos & Kontopoulos 1994). Valmi Formation is interdigitated laterally with Vounargos and Olympia Formations (Hageman, 1976; Kamberis, 1987). The Alpine basement of the NW Peloponnessus comprises Mesozoic-Early Cenozoic formations that belong to three different isotopic units (from west to east): Ionic Zone, Tripoli-Gavrovo and Pindos-Olones. Outcrops of these formations in the studied area, include flysch sediments (intercalations of sandstones, shales, conglomerates and limestones), marine limestones, schists, cherts and evaporates (Decourt, 1964; Kamberis, 1987).
Historical seismicity

The existence of descriptions regarding historical liquefaction occurrence in an area is one of the criteria that can be used in order to characterize the area as liquefaction prone zone. Thus, the historical seismicity of an area can help to the delineation of such zones. In our case, at the North-Western part of Peloponnesus, at least two earthquakes induced liquefaction surface manifestations; the 1988 Bartholomio event and the 1993 Pyrgos one.

In particular, the earthquake of October 16, 1988 triggered liquefaction phenomena such as ground fissures with ejection of sand-water mixture and sand volcanoes. According to Lekkas (1991) and Papadopoulos & Profis (1990), liquefaction-induced ground disruption was observed at the western bank of the river Pinios, about 400m from the sea shore and to the east of the area of Kastro. Moreover, at the area of Bartholomio, according to eye-witnesses water and sand was ejected from fissures at the fields creating sand craters with diameter up to 60cm. The 1993 Pyrgos earthquake, caused liquefaction phenomena in the area of Spiantza, close to the river Alfios (Lekkas, 1994). Mixture of sand and water was ejected form ground fissures with length up to 30m and created sand craters with diameter up to 50cm.

However, though these two events occurred in the vicinity of the studied area, no liquefaction surface evidences were observed at the sites where ground failures triggered by the last event.

Liquefaction-induced ground disruption

The most characteristic secondary effects triggered by the event of June 8, 2008 were the liquefaction manifestations. Impressive sand volcanoes and vent fractures were observed in many places, both at the areas located to the north (Kato Achaia, Alikes, and Nisi) and to the south from the epicentre at the banks of the river Pinios and at the shore of Lake Pinios. These liquefaction-induced ground failures appeared to be concentrated in areas formed by alluvial deposits.

![Figure 1. Map showing the distribution of the liquefied sites and the epicenters provided by NOA and AUTH](image)

Particularly, the most characteristic liquefaction phenomena were reported at the shore of the Lake Pinios, close to the village Roupakia, about 9 Km from the epicentre as it was defined by NOA. At this site we observed typical examples of liquefaction surface evidences; 2 sand-
mud boils with diameter up to 85cm and 3 smaller ones with diameter up to 70cm each, vent fractures with length more than 5 meters and width up to 15 cm and sand volcanoes with diameter up to 17 cm (figure 2). Moreover, a lateral spreading at the banks of the river was observed.

![Figure 2. Liquefaction surface evidences at the site Roupakia. Sand boils with diameter up to 85cm (up left); Vent fractures 85cm (up right); lateral spreading towards the river (down left); Sand volcanoes (down right)](image)

Close to this site and approximately at the same epicentral distance, is located the site of Kalivia. At this area, fine grained material was ejected from ground fissures as it is shown in figure 3.

Few kilometres to the south, at the banks of the river Pinios, small ground cracks were observed from which coarse grained material was ejected. At the same place, a horizontal displacement of 1-2 cm towards the river was observed (figure 3).

![Figure 3. Liquefaction surface evidences at the site Kalivia and at the banks of the river Pinios. Ejection of sand-water mixture at the shore of Lake Pinios (site kalivia); Ejection of sand-water mixture at the banks of Pinios river.](image)

The other sites where liquefaction phenomena were observed are located northern to the epicenter. The most impressive ones were mapped at the sea shore of the village Kato.
Achaia (figure 4) where ejected sandy grey material formed vent fractures with length from 50cm to 4 meters and width up to 22cm and sand volcanoes with diameter up to 8 cm in an area of 1km². From this area, samples from the ejected material were collected in order to perform laboratory tests regarding its grading characteristics. Moreover, at the same site two ground cracks with horizontal displacement of 4cm toward the sea and vertical subsidence of 2cm were mapped. The mean direction of these cracks was parallel to the coastline. Furthermore, at a distance of 600 meters, towards the mainland, ejection of grey sand was observed.

Figure 4. Formation of vent fractures of 4 meters long (left) and vent fractures with 12cm width (right) at the sea shore of Kato Achaia

Sand volcanoes and lateral spreading were observed at the river mouth of a torrent at a site called Alikes (figure 5), located 2 km western from the village of Kato Achaia. The diameter of the volcanoes ranged from 4 to 12 cm while from small scale cracks on the pavement, sandy material was ejected. Few meters distance from this site, an opening on the asphalt pavement with 3m length and 8cm width was triggered by the event.

Finally, close to the village Nisi, where surface rupture of 20cm vertical and 18 cm horizontal displacement were mapped, a small sand volcano was observed (figure 5).

Figure 5. Liquefaction manifestations at the site Alikes (left) and Nisi (right)

Structural damages that could be induced by the liquefaction of the subsoil layers were observed at the waterfront area of the village Vrahneika, at an epicentral distance of 25 km. In this area, the pavement was cracked and the lifelines were damaged. The mean direction of the cracks was parallel to the coastline while their length was measured up to 500 meter. The horizontal displacement ranged from 3cm to 7cm while in some places a vertical displacement of 3cm was reported (figure 6). However, no clear evidence of liquefaction such as ejection of material from the cracks or/and creation of sand volcanoes was observed at this area.
Performing back-analyses for the evaluation of liquefaction susceptibility

In order to assess the liquefaction susceptibility in an area, several criteria must be examined. According to Kramer (1996), historical, geologic and compositional data should be tested regarding the liquefaction susceptibility and potential of an area. In this study, we examined the susceptibility of the sites where liquefaction phenomena were observed by the application of the above criteria.

Empirical relationship of earthquake magnitude versus epicentral distance

The maximum epicentral distance of a liquefied site that can be triggered by an earthquake magnitude M can be estimated using empirical relationships. Three studies have been performed, regarding this issue, concerning the Aegean region and specifically Greece and relatively correlations were proposed by Ambraseys (1988), Papadopoulos and Lefkopoulos (1993) and Papathanassiou et al. (2005). In this study, we took into consideration the upper bound curves (for Greece and for the Aegean region) that were proposed by Papathanassiou et al. (2005) for the assessment of the liquefaction susceptibility of an area.

The estimation of the epicentral distances, of the sites where liquefaction phenomena were observed, was performed using the focal parameters of the event as they were published by the NOA (National Observatory of Athens, Institute of Geodynamics) and the AUTH (Aristotle University of Thessaloniki, Seismological Station). The epicentral distances range from 8 to 25 km based on NOA parameters and from 4 to 27 km based on AUTH data and they are listed in Table 1. Afterwards, the values of the distance of the liquefied sites were correlated to the M of the earthquake and they were plotted in the diagram (figure 7) for examine the susceptibility to liquefaction.

<table>
<thead>
<tr>
<th>Site</th>
<th>NOA focal parameters</th>
<th>AUTH focal parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pinios river</td>
<td>15</td>
<td>11</td>
</tr>
<tr>
<td>Roupakia</td>
<td>9</td>
<td>6</td>
</tr>
<tr>
<td>Augi</td>
<td>13</td>
<td>11</td>
</tr>
<tr>
<td>Alikes</td>
<td>19</td>
<td>24</td>
</tr>
<tr>
<td>Kato Achaia</td>
<td>19</td>
<td>23</td>
</tr>
<tr>
<td>Vrahneika</td>
<td>25</td>
<td>27</td>
</tr>
<tr>
<td>Kalivia</td>
<td>9</td>
<td>4</td>
</tr>
<tr>
<td>Nisi</td>
<td>10</td>
<td>12</td>
</tr>
</tbody>
</table>

As it is shown in figure 7, the sites where liquefaction phenomena triggered by the event of June 8, 2008 are plotted within the area that is defined as liquefiable zone by Papathanassiou et al. (2005). Thus, based on this back-analysis we concluded that the earthquake-induced liquefaction at these sites could be predicted based on the proposed diagram.
Laboratory results

Few days after the earthquake, field investigations were taken place. During these investigations ejected samples were collected from sand craters and vent fractures in the areas of Kato Achaia and Roupakia, with a view to examine their compositional characteristics that include grain size distribution, liquid limit and Plasticity index (Kramer, 1996). The laboratory testing of the collected material was performed at the Laboratory of Engineering Geology and Hydrogeology of the Department of Geology at the Aristotle University of Thessaloniki.

The three collected samples Rou1, Rou2, Rou3 from the shore of lake Pinios are classified as silty sand (SM). The fines content of these soils are 24%, 30% and 21%, respectively. The material that was collected from vent fractures and sand boils in Kato Achaia, (Kac1, Kac2) is classified as fine grained sand (SP); the content of clay and silt is 8% and 5%, respectively.

The results of grain size analysis of the samples are plotted to diagrams and compared to the proposed curves by Tsuchida (1971) for well graded soils and for soils at uniform grading. As it is shown in figure 8 and figure 9, the grain sizes distribution curves of the materials plotted within the suggested range of possibility of liquefaction, concluding that these diagrams can still be used for the prediction of the occurrence of liquefaction-induced ground disruption at one site.

Figure 8. Comparison among the grain size distribution curves of the collected samples Rou1, Rou2 and Rou3 and boundaries curves for most liquefiable soils suggested by Tsuchida (1971)
Results and Discussion

The earthquake of June 8, 2008 triggered secondary effects that were spread in a wide area. The most characteristic of them were liquefaction-induced ground failures, appeared to be concentrated in areas formed by alluvial deposits.

Large scale liquefaction surface evidences as sand boils, vent fractures, sand volcanoes and ejection of sand-water mixture were observed at the waterfront area of village Kato Achaia, Alikes to the north of the epicenter and to the shore of the lake Pinios (close to the village Roupakia) to the south of the epicenter. Smaller scale liquefaction phenomena were reported at the site Nisi and at the banks of the river Pinios.

In order to examine liquefaction susceptibility, at the sites where liquefaction phenomena were observed, back-analyses were performed. Initially, the susceptibility was evaluated using published empirical relationships correlating their epicentral distances with the earthquake magnitude $M$. The distribution of the liquefied sites, on the published diagram, is in agreement with the delineated liquefaction-prone zone, indicating the usefulness of this method to the preliminary evaluation of the liquefaction susceptibility.

Afterwards, ejected samples from the sites Roupakia and Kato Acahia were collected in order to examine the liquefaction susceptibility of the soil layers. The distribution curves, outcome from the grain size analyses, of the ejected material plot within the area defined as high possibility to liquefaction by Tsuchida (1971), concluding that these soils are susceptible to liquefaction regarding their grain size.

References

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