Liquefaction phenomena in the Aegean broader area and empirical relations of magnitude versus distance

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Keywords: liquefaction, earthquakes, Mediterranean region, magnitude

Introduction

After the Niigata earthquake of 1964 in Japan several researches worked on the phenomena of liquefaction and its sequences. For the evaluation of liquefaction potential of an area, several criteria must be examined, such as historical, geologic, compositional and state criteria. Information about liquefaction behavior that has come from field reports shows that liquefaction often recurs at the same location when soil and groundwater have remained unchanged. Thus, liquefaction case histories can be used to identify specific sites, or more general site conditions, that may be susceptible to liquefaction in future earthquakes.

The seismicity of the Eastern Mediterranean-Middle East region as well as the abundant cultural references on it consist a combination that can help the earth scientists investigate the appearance of liquefaction phenomena. In this report 257 liquefied sites occurring in this region from 373 B.C. to 2003 have been re-evaluated and presented. Afterwards, these data have been examined to estimate relations of magnitude versus distance. These relations show that the maximum epicentral distance increases along with increasing magnitude. These equations improve the relations proposed by other authors.

Data

The coordinates of the area that has been examined are (34°-43 °N, 18 ° -31 °E) and a map of is being shown in the figure 1. The circles (orange) indicate the epicenters of the earthquakes that have triggered liquefaction and the stars (red) indicate the liquefied sites.

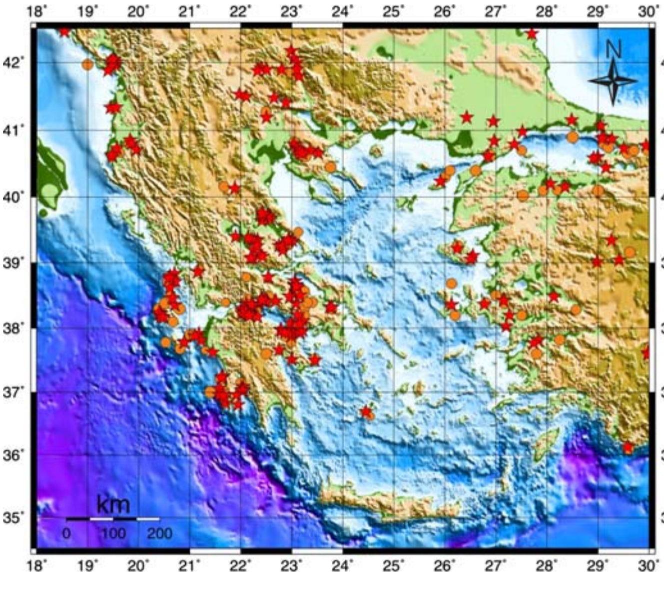

Figure 1. Map of liquefied sites (stars) and earthquake epicenters (circles).

In many cases, the focal parameters of the earthquakes have been estimated differently among the scientists causing problems in the evaluation of the Re. Especially in the small magnitudes events, this disparity is very important for the calculations of Re. In order to avoid the problem of the unevenness, the coordinates of the epicenters have been collected from one source, by Papazachos & Papazachou (1997), while being also enriched by Ambraseys (1988)

Liquefaction phenomena triggered from earthquakes are observed in places of deltaic, lake or alluvial deposits. The susceptibility of older soil deposits to liquefaction is generally lower than that of newer deposits. The types of liquefaction phenomena are earthquake induced ground failures on level ground caused by lateral spreading, loss of bearing capacity and ground settlements leading to the eruption of sand boils and mud volcanoes.

As we can see in figure 1, the frequency of liquefaction phenomena triggered from earthquakes is very high at the Gulf of Corinth and at the Sea of Marmara. The high seismic activity of these two areas and the soil conditions (deposits) in combination with the numerous written reports during all centuries give to the researches the possibility for further investigation. Another area of high potential for liquefaction is the region of Ionian island and the area of Izmir.

A disproportional distant site at which liquefaction was observed relatively to the magnitude is the 1861 earthquake in the epicentral area of Aeghio (Gulf of Corinth). In this case, sand boils were observed in the village of Kalamaki, 85 Km far from the epicenter. J. Schmidt (1867) in his study descripts the appearance of sand boils spouting muddy material 12 or 15 min after the event.

The Murefte (Western Anatolia) earthquake of 1912 Ms=7.6 and the Kresna (SW Bulgaria) earthquake of 1904 Ms=7.1 triggered the most distant liquefaction sites at 210 Km and 118 Km relatively. In the first case (1912) the epicenter of the earthquake was nearby the Gulf of Saros. The Anatolian fault has been activating, explaining why the magnitude is so high. The liquefaction sites were observed not only in the epicenter area but also in the coastland of Sozopoli, in Bulgaria. The Kresna earthquake of 1904 with magnitude Ms=7.1 caused liquefaction in many regions. This happened because the epicentral area has been formed from river deposits with high susceptibility in liquefaction.

The minimum earthquake magnitude (Ms=5.2) triggered liquefaction reported in 1992 on the island of Milos(Aegean Sea). The epicentral distance of liquefaction was anomalously long, Re=12 km. Ground tension cracks with lengths up to about 30 m and an ejected mixture of water and softy sandy material were observed. The explanation for this abnormally liquefaction distance relies on the occurrence of strong ground acceleration at favorable soil conditions in the island. (Papadopoulos 1993).

The maximum epicentral distance for earthquakes in Greece is rather small to those observed in the surrounding region. This happens for two reasons: the lack of big events and the geomorphologic conditions. With the exception of the area of Thessaly, in Greece we don't find large areas susceptible to liquefaction in contradiction to the surrounding region (Kresna). Also the big events in Greece ($Ms \geq 7$) are rarely and most of them are offshore.

Magnitude – Distance relations

Magnitude versus maximum epicentral distance

The correlation between the maximum epicentral distance Re at which liquefaction has been reported and associated earthquake magnitude M has been investigated from several authors. Kuribayashi & Tatsuoka (1975), using Japanese data from earthquakes that have caused liquefaction, showed that the maximum epicentral distance at which such phenomena have been observed may be approximated by

$$\mathrm{Log}\,(Re) = 0.77\,(M) - 3.60 \qquad \text{Re in Km} \qquad (1)$$

Ambraseys (1988) uses 137 cases from all around the world, correlated moment magnitude Mw both with epicentral distance Re and fault distance Rf:

$$Mw = -0.31 + 2.65 \times 10^{-8}\,Re + 0.99\,\log\,(Re) \qquad \text{Re in cm} \qquad (2)$$

$$Mw = 0.18 + 9.2 \times 10^{-8}\,Rf + 0.9\,\log\,(Rf) \qquad \text{Rf in cm} \qquad (3)$$

According to this paper, for each value of magnitude Mw, Re and Rf are the maximum distance within which liquefaction is likely to occur (with some exceptions).

Papadopoulos and Lefkopoulos (1993) updating the data collected by Ambraseys by adding 30 new cases from earthquakes from Greece and 3 world cases provided the following equations:

$$Mw = -0.44 + 3 \times 10^{-8} Re + 0.98 \log (Re) \qquad \text{Re in cm} \qquad (4)$$

$$Mw = -2.5 \times 10^{-3} + 9.25 \times 10^{-8} Rf + 0.9 \log (Rf) \qquad \text{Rf in cm} \qquad (5)$$

Considering only the Greek data they calculated the relationships:

$$Ms = 3.686 + 1.584 \log (Re)\ (Ms>5.9) \qquad \text{Re in km} \qquad (6)$$

$$Ms = 5.647 + 0.181 \log (Re)\ (5.8<Ms>5.9) \qquad \text{Re in km} \qquad (7)$$

$$Ms = 5.623 + 0.209 \log (Rf)\ (5.8<Ms>5.9) \qquad \text{Rf in km} \qquad (8)$$

Finally Galli (2000) re-evaluated seismic parameters of the Italian historical earthquakes, together with the location of 317 indications of liquefaction features and provide the following relationships:

$$Ms = 1 + 3 \log (Re) \text{ for data before 1900} \qquad \text{Re in km} \qquad (9)$$

$$Ms = 1.5 + 3.1 \log (Re) \text{ for data after 1900} \qquad \text{Re in km} \qquad (10)$$

In this paper are presented equations produced by the re-evaluation of 257 liquefied sites caused by 89 earthquakes that have triggered liquefaction in the Eastern Mediterranean region and the Middle-East. In figure 2 the plotted data is being shown in a diagram of epicentral distance versus magnitude Ms. The proposed equation in this paper for the maximum epicentral distance Re of liquefied sites associated to earthquake magnitude Ms is:

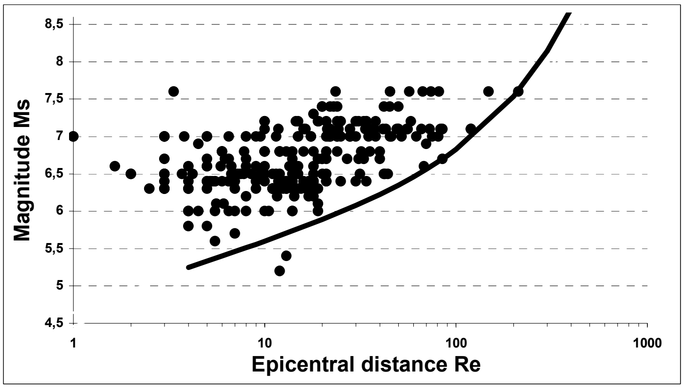

Figure 2. Magnitude versus epicentral distance (Re). With circles are the data and the solid line is the critical line proposed at the present paper.

$$Ms=0.6933+4.655 \times 10^{-8} Re+0,8907 \log(Re) \qquad \text{Re in cm} \qquad (11)$$

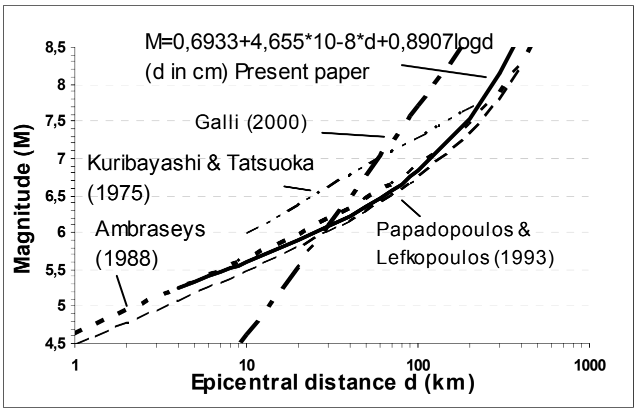

Figure 3. Comparison among the different curves provided by the previous authors and the curve presented in this paper.

The proposed curve is plotted with data until the magnitude Ms=5.2 since this is the smallest earthquake which caused liquefaction in the study area. On the contrary, the curves of the other authors continue until smallest magnitude of earthquakes. Figure 3 compares the curve presented in this paper [equation (11)] with those provided by Kyribayashi and Tatsuoka [(1975), equation (1)], Ambraseys [(1988), equation (2)], Papadopoulos and Lefkopoulos [(1993), equation (4)] and Galli [(2000), equation (10)].

Magnitude versus fault distance

For small-magnitude earthquakes with liquefaction sites clustering together within a small area, there is a possibility of bias in estimating Re. This occurs due to small location errors of the epicentre which become big errors in the estimate of Re. Thus Youd (1977) and Youd and Perkins (1978) introduced the idea of measuring the distance from the fault Rf rather than from the epicenter for liquefaction occurred during several earthquakes. Rf is defined as the maximum distance of liquefaction from the seismic source and is, in general, the fault distance.

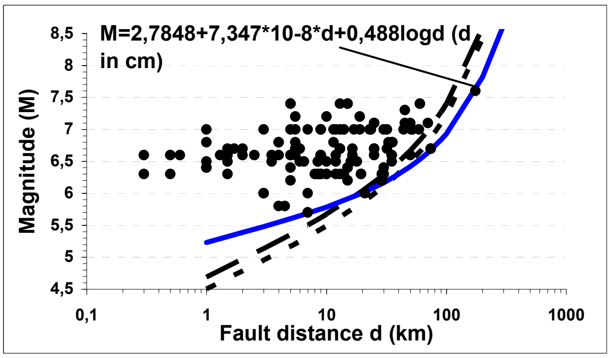

Figure 4. Magnitude versus Fault distance (Rf). With circles are the data and the solid line (blue) is the critical line proposed in the present paper. The dashed lines (1) and (2) are the curves proposed by Ambraseys and Papadopoulos & Lefkopoulos.

In this paper is presented the following equation [12] for the maximum fault distance of liquefied sites associated to earthquake magnitude Ms:

$$Ms = 2{,}7848+7{,}347 \times 10^{-8}\, Rf+0{,}488\log(Rf) \qquad Rf \text{ in cm} \qquad (12)$$

The maximum fault distance Rf at which liquefaction has been occurred is 175 km for an earthquake of Ms=7.6 (1912 event of Murefte). Figure 4 shows a plot of Rf as a function of surface magnitude Ms. At the same figure the curves provided by Ambraseys (1988) and Papadopoulos & Lefkopoulos (1993) are compared to the currently proposed curve of this paper.

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