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**An Overview of Earthquake Related
Liquefaction Events in Italy**

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AN OVERVIEW OF EARTHQUAKE RELATED LIQUEFACTION EVENTS IN ITALY

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Foreword

This report was prepared by Mr Edoardo Borgomeo (edbo@hotmail.it) during the summer pause of Imperial College (London, UK) lectures.

Mr Borgomeo have joined the Istituto Nazionale di Geofisica e Vulcanologia (Italian Institute of Geophysics and Volcanology) for an internship under the supervision of Dr. Giuseppe Di Capua (giuseppe.dicapua@ingv.it) and Prof Silvia Peppoloni (silvia.peppoloni@ingv.it).

This internship was an opportunity to gain an understanding on the functioning of a research institute and on the tasks a researcher has to undertake in the creation of a scientific publication. The result of the internship is presented in the following report that investigated the phenomenon of liquefaction under seismic conditions.

We would like to thank Dr Lidia Lonergan, Imperial College, for the advise given.

This report was also reviewed by Dr Alessandro Pagliaroli (Consiglio Nazionale delle Ricerche - National Research Council - and Sapienza University of Rome: alessandro.pagliaroli@uniroma1.it) and Prof Giovanna Biscontin (Texas A&M University – Zachry Department of Civil Engineering: gbiscontin@tamu.edu).

Introduction

The most serious direct effect of earthquakes on buildings and structures is ground shaking. However earthquake shocks might pose other hazards in the form of soil liquefaction, which can result in considerable financial losses. Some soils such as quicksands and quickclays can give rise to major problems when disturbed by ground shaking. The ground vibrations produced by an earthquake lead to a decrease in the effective stress and in the shear strength of the soil which in turn trigger the liquefaction (Figure 1).



Figure 1. Aerial view of leaning apartment houses in Niigata produced by soil liquefaction. Most of the damage was caused by cracking and unequal settlement of the ground such as is shown here. About 1/3 of the city subsided by as much as 2 meters as a result of sand compaction [from: http://earthquake.usgs.gov/regional/world/events/1964_06_16.php].

1. Physical aspects

The phenomenon of liquefaction can be fully understood by considering the effective stress relationship proposed by Terzaghi in 1936. This principle asserts that in a saturated soil the tensional state is determined by the difference between the total normal stress (σ) and the pore water pressure (u), which is applied with the same intensity in all directions. The difference $\sigma - u = \sigma'$ is called effective stress and is responsible for all the changes, due to compression, distortion etc., that occur in the soil mass [Colombo and Colleselli, 2003; Crespellani et al., 1988]. If the pore fluid pressure is hydrostatic, i.e. the water does not flow, the hydraulic head remains constant and the pore water pressure linearly increases with depth. However as soon as the soil mass is subjected to a shock or some other external disturbance the hydraulic head difference (Δh) changes and the pore fluid starts to flow according to the hydraulic gradient, which means that the fluid will flow from a point of greater hydraulic head to a point of lower hydraulic head (according to the principle of conservation of energy). Considering that the loss of hydraulic head occurs along a flow path of length L , it is possible to define the hydraulic gradient as the loss of hydraulic head per unit length:

$$i = \frac{\Delta h}{L}$$

The hydraulic head difference Δh represents the energy lost by the fluid flow due to the frictional resistance of the soil grains [Gonzalez de Vallejo, 2004]. If the resistance to filtration produced by the soil grains is less than the erosional force of the fluid, the soil grains can be transported away (eroded) by the flow. The resistance to filtration depends on the cohesion, sorting and level of compaction of the material, while the erosional force of the fluid depends upon the hydraulic gradient. The hydraulic head is influenced by the piezometric height (z) of the point concerned and by the pore fluid pressure (u) at that point. During an earthquake the pore water pressure rapidly increases thus inducing an increase in the hydraulic head difference. Consequently the hydraulic gradient increases until it reaches a critical value at which the effective pressure σ' becomes zero [Craig, 2004; Crespellani et al., 1988]. At this stage the soil loses all bearing capacity and starts behaving like a viscous fluid. In fact, as water flows through the soil particles, it loses hydraulic head, which is transferred as energy to the particles past which it is flowing, creating a hauling effect (seepage forces) on these same particles. If the loss of head and the strength of the water flow are greater than the resistance of the particles to filtration, the hydraulic gradient reaches the critical point at which the particles start being transported by the water (Figure 2).

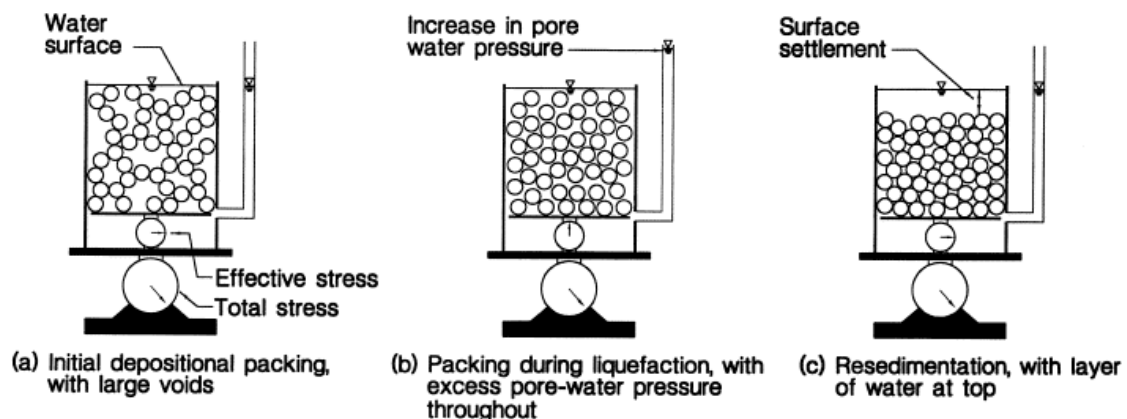


Figure 2. Changes in packing of sediment grains caused by liquefaction [Obermeier et al., 2005].

Some conditions have to be met in order for this phenomenon to occur. First, the material concerned must be saturated and loosely packed [Gonzalez de Vallejo, 2004]. Second, on disturbance, the shaking has to produce an increase in pore fluid pressure great enough to overcome the forces acting between the grains. In materials with high permeability the neutral pressure (i.e. pressure carried by the water) cannot be built up as the water can escape very rapidly; hence the third condition requires that the material has a low permeability. These conditions are usually fulfilled by fine sands or silts, characterized by low levels of cohesion and density, which makes them more susceptible to seepage forces [Bell, 1998]. The low levels of intergranular cohesion and compaction induce these materials to contract under shear stress conditions. During an earthquake the time interval during which the shear is applied is extremely short compared to time required for the water to drain, thus contraction cannot occur and pore pressure increases and effective stress decreases. When the pore pressure equals the total stress the effective stress is reduced to zero. At this stage the soil will lose its shear strength and it can be liquified, i.e. it will start to flow.

2. Liquefaction susceptibility of soil

The liquefaction susceptibility of a soil depends upon the properties and state of the soil subjected to the shaking and to the subsoil geometry [Seed and Silver, 1972; Seed et al., 1977].

As outlined in the previous paragraph, liquefaction is most commonly observed in loosely compacted, saturated deposits of cohesionless soils subjected to strong ground motions in large magnitude earthquakes [Port and Harbour Research Institute, 1997]. Liquefaction is not observed in unsaturated soils because the total fraction of water in the soil is too low to build up enough pore fluid pressure, even under rapid compression. The cohesion between the grains is a factor that increases the liquefaction resistance of a soil and it might be enhanced by particle cementation and soil fabric. Furthermore the age of the deposit usually gives a rough estimate of the tendency to liquefy of a soil; in fact soils deposited before the Holocene (i.e. about 10,000 years ago) are usually not prone to liquefaction [Craig, 2004]. This can be explained by observing that older soils are more over consolidated with respect to younger deposits, which have been subjected to lower overburdens. However some deposits might have been loosened by previous shakings, indicating that the stress history is also an important factor in determining the tendency of a soil to liquefy [Obermeier et al., 2005].

In general, the greater the confining stress the greater the resistance of a soil to liquefaction, as the increase in overburden pressure, which depends on the depth of the sediment, produces a densification of the soil grains thus eliminating the void spaces in between the particles and increasing their frictional resistance. The shape of the clasts composing the deposit and their degree of sorting also have to be taken into account because well sorted deposits with spherical clasts are more prone to liquefaction than poorly sorted deposits with angular clasts that present more stable structures because of the interlocking disposition of the grains [Bell, 1998].

Permeability also affects the liquefaction susceptibility of a deposit because, as already stated, it governs the ease with which water can escape the deposit during shaking. The permeability of the surrounding deposits is also important because they might impede the drainage of a more permeable deposit, thus inducing the accumulation of pore fluid pressure and liquefaction. Liquefaction then occurs most readily where thick, sand rich deposits are covered up by low permeability deposits and where the water table is very close to the ground surface [Obermeier et al., 2005]. Gravelly soils are in general less prone to liquefaction because of their high permeability, which allows water to flow away from the material before it generates great amounts of pore fluid pressure.

When a state of liquefaction is reached, i.e. when $\sigma = u$, liquefaction characteristics vary according to the density of the soil. Dense sands never change completely to a liquefied state because they are able to restore intergranular forces when sheared, even after the pore water pressure has exceeded the normal stress. However when the density of the sand becomes too low, permanent deformation and flow failure occur, so that any residual shear resistance is lost and the sand starts to behave like a fluid [Port and Harbour Research Institute, 1997]. The density criterion is very useful in the evaluation of the liquefaction susceptibility of a soil as no flow failure will normally be triggered by the liquefaction of medium and dense sands.

3. The liquefaction potential: magnitude–epicentral distance relationships

The primary factors controlling the liquefaction potential of a deposit are the nature and relative density of the soil, its field setting, its overall effective pressure and the duration and intensity of the earthquake shaking. The distinguishing characteristic between liquefaction potential and liquefaction susceptibility lies in the fact that the latter depends on permanent parameters, while the former depends also on the triggering factor given by the earthquake shaking [Liam Finn, 2001]. The characteristics and nature of the earthquake assume a great deal of importance, especially when a realistic assessment of risk posed by liquefaction is required. Much research has been done in the effort of establishing a relationship between earthquake magnitude and maximum epicentral distance. The review of scientific publications revealed that many empirical relations have been proposed on the basis of regional and worldwide data. Ambraseys [1991], by analyzing liquefaction cases from around the world, determined that the magnitude and epicentral distance were exponentially correlated, as the maximum epicentral distance at which liquefaction occurred increased exponentially for higher magnitude values. Results regarding maximum source distance to a site of liquefaction have been also discussed by Papadopoulos and Lefkopoulos [1993]. After reviewing the historical seismicity of Greece they reported at least 30 cases of liquefaction and stated that the lowest magnitude at which liquefaction occurred had values as low as 5. A further update in the research and an accurate estimation of the distance-magnitude equation was provided by Galli [2000]. The research carried out by Galli [2000] was based on Italian earthquakes integrated with worldwide data about liquefaction. The database for liquefaction occurrences in Italy showed how 76% of the liquefaction events occurred at macroseismic intensity values greater than 9-10 and that 46% liquefaction cases took place within 10 km of the epicenter and 90% within 50 km, suggesting a value slightly higher than 50 km as the maximum epicentral distance for earthquakes with intensities lower than 10. Extremely strong earthquakes (with magnitudes greater than 7) have induced liquefaction as far as 80 km from the epicenter. Galli [2000] has also proposed a graph of epicentral macroseismic intensity vs. epicentral distance which shows the distribution of the Italian liquefaction occurrences. This distribution is bounded by an exponential limit whose trend is similar to the bounding equations obtained by Ambraseys [1988] and Papadopolous and Lefkopolous [1993]. The equation proposed by Galli binds an area of liquefaction potential which is larger than the one proposed by other authors. In other words the limit proposed by Galli widens the magnitude/distance combinations at which liquefaction might occur, especially for low magnitude events (Figure 3).

Another contribution to the discussion on magnitude-distance relationships came from the review of historical and seismotectonic events in the broader Aegean region done by Papathanassiou et al. [2005]. Their research presents an updated database for the liquefaction occurrences in Greece, Turkey, Albania and Bulgaria. The dataset consists of 88 earthquakes whose majority took place in Greece. The bounding limit proposed by Papathanassiou et al. [2005] is in general agreement with the other equations proposed earlier. In this analysis particular relevancy has been given to the fact that sites that liquefied under past earthquakes will have a strong tendency to liquefy again. The repeatability of liquefaction occurrence is then confirmed by this catalogue and thus it can be used as a preliminary tool for liquefaction potential assessment. The majority of the researches proposed so far on the maximum distance-magnitude relationships have been based on simple regression lines. This method is certainly efficient as it gives a first, rough estimate of the requested equation, but nonetheless a more adequate number of liquefaction documented cases is needed to obtain a larger confidence interval during liquefaction potential assessment.

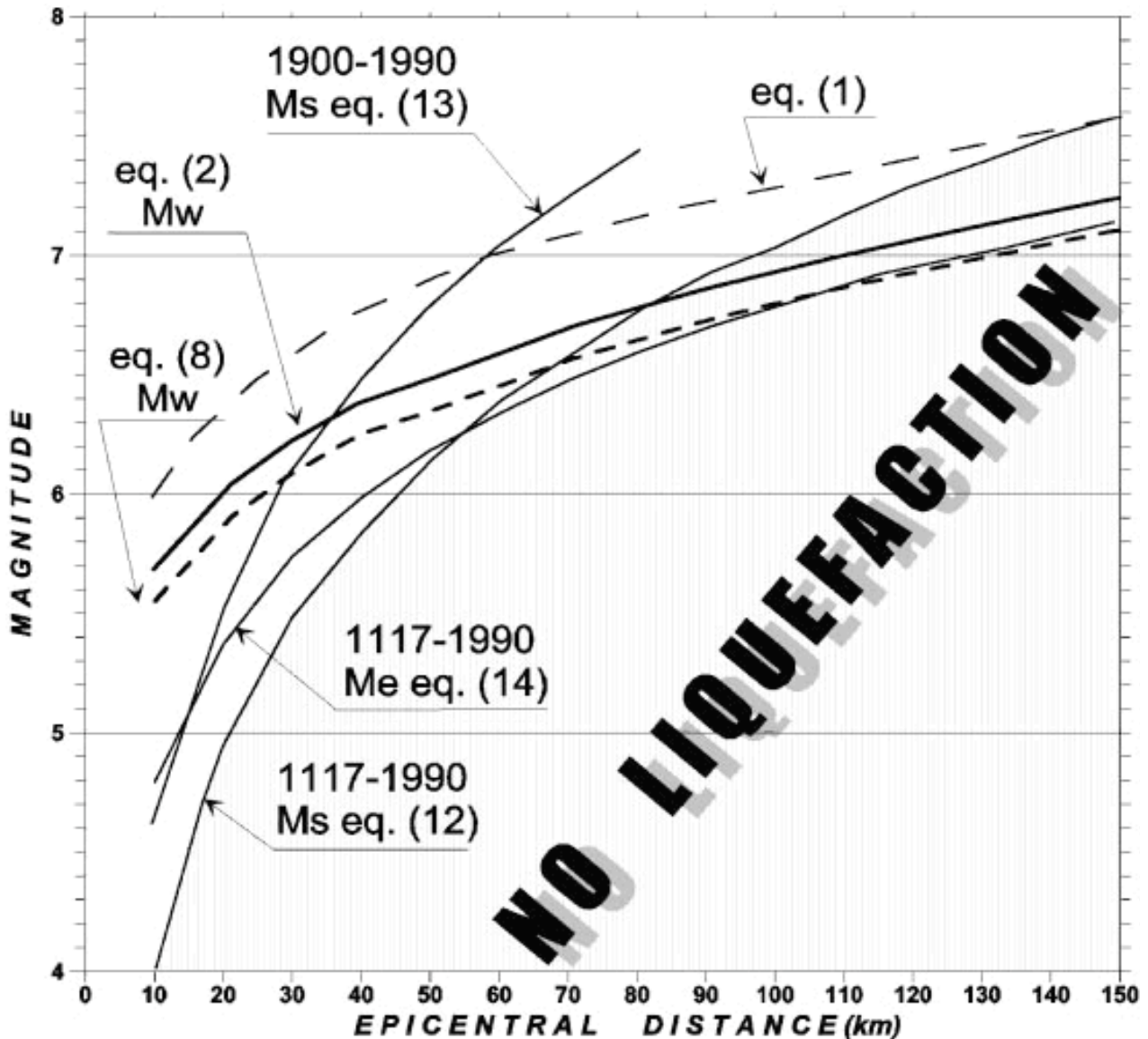


Figure 3. Comparison between the equations proposed by Galli [12-14], Kuribayashi and Tatsuoka (not in the reference list) [1], Ambraseys [2] and Papadopolous and Lefkopolous [8]. It is evident that the equations proposed by Galli widen the magnitude-distance combinations at which liquefaction might occur, especially for low magnitude events [from: Galli, 2000].

4. Liquefaction potential assessment

Liquefaction potential assessment is comprised in the seismic hazard analysis; however in some cases the liquefaction potential is not included in the framework of seismic hazard assessment. The frequent absence of liquefaction from the list of earthquake-related hazards is probably due to the dependency of liquefaction on many parameters, which are often difficult to estimate. In fact, liquefaction depends on both permanent factors and unpredictable, external and unstable factors. The permanent factors are determined by investigating the liquefaction susceptibility of a soil with identification and mechanical in situ tests, such as the Standard Penetration Test (SPT) and Cone Penetration Test (CPT) [Lenz and Baise, 2006]. These two techniques are widely applied to determine the relative density of the soil, which is the degree of “packing” of the sand. The SPT relates the blow counts with the relative density. A standard table is used to correlate SPT blows with relative density. The relative densities range from very loose to very dense. Very loose sands are highly susceptible to liquefaction, as the seepage forces can easily overcome the intergranular resistance to filtration. The CPT has the advantage of being more accurate in the measurement of the

properties and stratigraphy of a deposit, as it generates less vibrations and disturbances than the SPT [Liam Finn, 2001]. The grain size distribution needs also to be determined in order to calculate the uniformity coefficient, which gives, together with the saturation index, a good indication on the liquefaction susceptibility of a soil. The analysis of these parameters and the use of SPT and CPT tests are useful to evaluate the susceptibility of a deposit disregarding the earthquake magnitude, hence they provide practical information at the preliminary and planning stages of site assessment but are not detailed enough to be accepted as a final liquefaction potential assessment of a site. In other words these empirical testing has to be accompanied by simplified methods aimed at determining the role that the aggravating, unpredictable factors (i.e the seismic context, given by the earthquake magnitude and the epicentral distance, and the hydrogeological context) have on liquefaction potential. The simplified methods consist in estimating a safety factor F_L , which is defined as the ratio of the resistance to liquefaction and the stress induced by earthquake shaking [Seed and Idriss, 1971; Santucci de Magistris, 2005]. The resistance to liquefaction is expressed as the Cyclic Resistance Ratio (CRR) and it can be determined by CPT, SPT tests, or by measurements of shear wave velocity. The total stress induced by the earthquakes is expressed as the Cyclic Stress Ratio (CSR) and it's calculated by estimating the value of the maximum acceleration expected at the surface (a_{max}) in a given time interval [Liyanapathirana and Poulos, 2004; Crespellani et al., 2002]:

$$F_L = \frac{CRR}{CSR}$$

This simplified method is certainly more complete than the empirical testing alone because it takes into account not only the soil characteristics but also the earthquake features. Other methods used to assess the liquefaction potential of a soil are the numerical analysis methods that model all the phenomena induced by seismic waves propagation in a soil deposit including pore water pressure changes [Crespellani et al., 1988]. The parameters developed with the previous techniques can be used for a probabilistic approach to the liquefaction potential assessment that might provide some quantitative estimates on the tendency to liquefy. Trifunac and Todorovska [2003] suggested that the maximum epicenter-site distance for liquefaction can be estimated on the minimum incident wave energy, which is the lowest energy wave known to have liquefied a site. This value is then chosen on the basis of the observed data and also on the properties of the soil. The minimum incident wave method is clearly limited for hazard assessment in sites where liquefaction has already occurred since it is dependent on previously determined site parameters. In general the reliability of liquefaction potential assessment depends mostly on the quality of site characterization and on the synthesis of results from different procedures; in fact, an approach based on a single procedure should be avoided [Idriss and Boulanger, 2006].

5. Italian case histories of soil liquefaction: a brief description

The importance of the phenomenon of liquefaction as a potential hazard during earthquakes is demonstrated by the fact that liquefaction is responsible for 18% of all the ground failures occurred in Italy during earthquakes [Prestininzi and Romeo, 2000]. It follows that it is essential to examine the type of liquefaction features generated during earthquakes as they might help in characterizing the earthquake.

The most commonly observed effects of liquefaction are: sand boils or volcanoes formed by the venting on the surface of sand grains suspended in water; ground failures; ground motion, produced by differential motion of more rigid layers located above the liquefied strata, that can result in fracturing and general damage on the overlying structures; floating of underground structures, such as pipelines or tanks, that are lighter than the surrounding liquefied soil [Crespellani et al., 1988].

The significance of these phenomena as a potential hazard and source of damage is better explained with a few examples. Sand volcanoes, sand and water eruption and sinking of the earth's surface occurred during the 6/05/1976 earthquake ($M_w = 6.43$) in the Friuli region, in the North-Eastern part of Italy (Figure 4). During this event some buildings sank about 30 cm into the ground and other buildings showed swelling of the lower ground floors for as much as 40 cm. In the epicentral region other buildings resulted damaged by differential settlement due to liquefaction [Berardi et al., 1991].

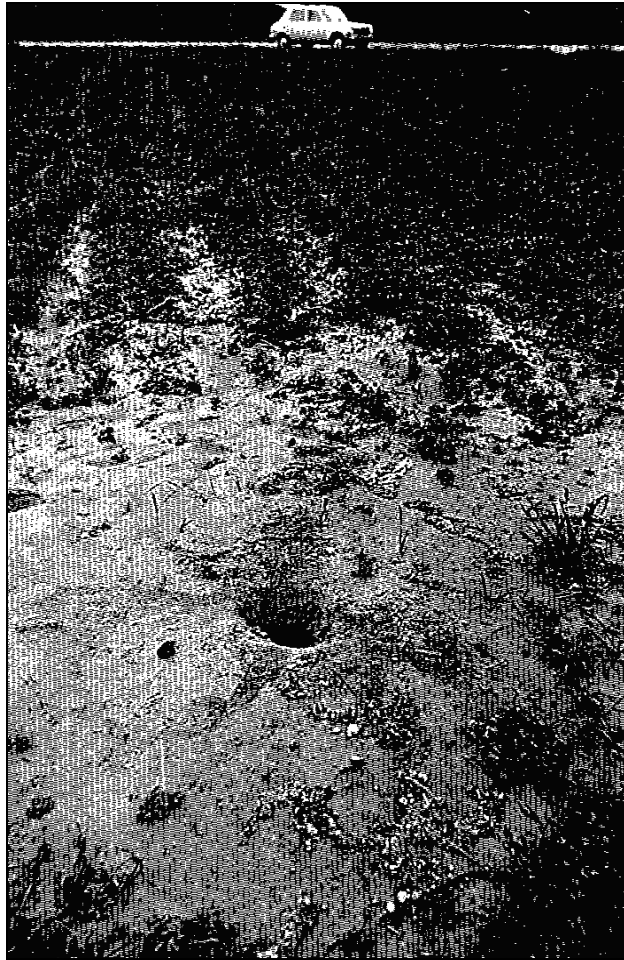


Figure 4. Sand boils produced by mixed water and sand venting during the Friuli earthquake [Crespellani et al., 1988].

The effects of liquefaction were minor in another disastrous event, the Irpinia earthquake ($M_w = 6.89$) of the 23rd of November 1980, which had nonetheless a greater magnitude than the Friuli earthquake. In this case soil liquefaction was limited to small sinking of the ground surface and ground fissuring [Berardi et al., 1991], probably because the volcanic deposits of the area were more resistant to liquefaction and shear stress than the alluvial and aeolian deposits of the Friuli region. The ground effects of liquefaction have also been extensively examined by Guarnieri et al. [2007] whose research focused in identifying and describing structures produced by historical earthquakes in the Etna region, in the province of Catania (Eastern Sicily). This work gave an interesting perspective on the liquefaction structures induced by historical earthquakes. They examined two different locations, the Minissale trench and the Agnone trench, which were subjected to successive liquefaction events. The most frequently encountered structures in their analysis were dikes, filled with clasts and sand, that rose from their original setting as a result of upward seepage forces that overcame the resistance of gravity, dome-like structures and soil caps developed by dikes overtopped by low permeability clay layers, extended structures formed by boudinage of sand layers as a consequence of seismic shaking, lateral spreading of the fine grained low permeable soils due to the liquefaction of the underlying layers. The Italian database for liquefaction occurrences produced by historical earthquakes has been expanded by Galli [2000]. According to this database the most commonly observed liquefaction induced ground failure in Italy is ground fissuring, which amounts to 26% of all types of failure. Other commonly observed features include mixed water and sand venting [18 %] and mud volcanoes (17%). These last two types of failure are usually related, meaning that they are often seen occurring together at the same site.

6. Mapping of Italian liquefaction phenomena on Google Earth

This study is coupled with the construction of a map (Figure 5) on Google Earth displaying the geographical distribution of liquefaction events in Italy. The distribution is based on the database produced by Galli [2000] and it presents information on the type of failure observed at each site and the characteristic of the associated earthquake. In particular the parameters specified for each entry are:

- reference number as indicated in the database by Galli [2000] and name of site where liquefaction was observed;
- date of the earthquake that triggered the liquefaction event;
- earthquake macroseismic intensity at the epicenter (I_0);
- earthquake magnitude at the epicenter (M_e);
- distance (in kilometers) between liquefied site and epicenter;
- macroseismic Intensity at the liquefied site (I_s);
- type of liquefaction features observed using the classification indicated by Galli [2000].



Figure 5. Geographical distribution of liquefaction events in Italy visualized on Google Earth. It is possible to individuate the clustering of events in the Calabria and the Friuli regions.

The types of liquefaction features observed have been divided in 8 broad categories according to the methodology used by Galli [2000]. Some of the events recorded in the database by Galli [2000] have not been located on the map because there was no indication of their exact position, in terms of geographical coordinates. Another event has been added to the database with the number 318. This liquefaction event has occurred in Vittorito during the 6.04.2009 earthquake in Abruzzo (Figure 6). The data on the location of this event and the type of liquefaction features observed have been provided by Prof. Filippo Santucci de Magistris.

During the transcription of the liquefaction events on the map from the database produced by Galli [2000] it was possible to find some inaccuracies regarding the coordinates or the dates of some events:

- the event 44 might have wrong coordinates, as it appears to be located in the Southern Mediterranean Sea, far from land;
- the event 116 has presumably a wrong date because it doesn't agree with the chronological order with which the other events have been positioned;
- the event 201 displays the same kind of problem as the previous case;
- the event 147 might have a wrong longitude as it appears to be located near the Caspian Sea;
- the event 119 might have wrong coordinates, since it is placed off the coast of Calabria.



Figure 6. Sand boils observed at Vittorito, produced by the L'Aquila earthquake of 6.04.2009 [<http://www.rete5.tv/images/stories/Ambiente/vulcanetti.jpg>].

7. Conclusions

From the geographical distribution of the liquefaction events mapped on Google Earth it is immediately clear that Calabria is the region most deeply affected by liquefaction (Figure 7). This is probably due to the fact that in this region saturated sandy deposits are located in correspondence of active faults that generate high magnitude earthquakes. One other region that has experienced several liquefaction

events is Friuli. In this case most of the events were linked to the 1976 earthquake. As it appears from the graph, some regions with high seismicity, such as Campania and Sicily, have experienced fewer liquefaction events than Calabria and Friuli because, probably, the seismogenic faults are not located near deposits susceptible to liquefaction.

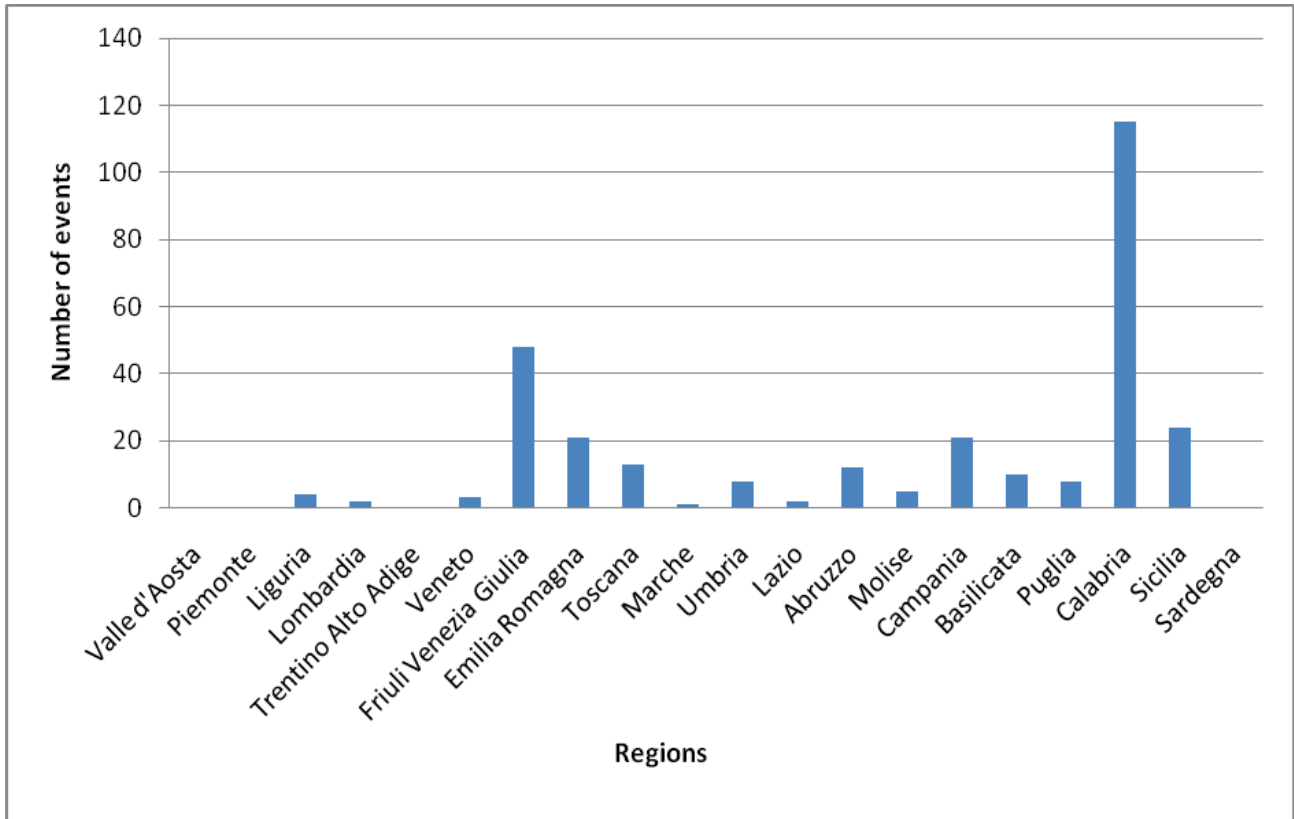


Figure 7. Geographical distribution of liquefaction events.

In the future further work needs be undertaken in the attempt of recognizing the relationship between the geographical distribution of liquefaction events and the geology of the areas affected by this phenomenon. The construction of a liquefaction hazard map based on the data by Galli [2000] wouldn't provide a secure tool for liquefaction potential assessment but it would integrate the assessment techniques previously outlined.

Appendix

An effort has been made to elaborate a simple statistical analysis of the type of liquefaction observed to determine which type is more frequently observed.

The total number of liquefaction produced ground failures registered in the database by Galli [2000] is 789. This number is greater than the number of localities where liquefaction related ground failures have occurred because at some localities more than one type of failure has been observed.

The graph (figure A) displays the frequency distribution of the 8 categories of liquefaction induced failures. The types of failures have been subdivided according to the classification proposed by Galli [2000]. The classification can be read as follows:

- A1: Ground fissures;
- A2: Water emission;
- A3: Mud, sand and gravel venting;
- A4: Mixed water and sand venting (sand volcanoes);
- A5: Mud volcanoes;
- B: Surface deformation;
- C: Differential settlement of building;
- D: Liquefaction evidence in a broad sense or without description.

The most frequently observed types of failures are phenomena related to ground fissuring. In particular ground fissures occur 27% of the time liquefaction phenomena are observed. Sand volcanoes and mud volcanoes are also very frequent events associated with liquefaction and they mostly occur together amounting in total to more than 36% of all the liquefaction features. The high frequency of sand and mud volcanoes as types of liquefaction might be influenced by the fact that they are very easily identified and thus they are recorded more often in registers. Liquefaction phenomena responsible for serious damage and differential settlement of buildings occur roughly 4% of the time.

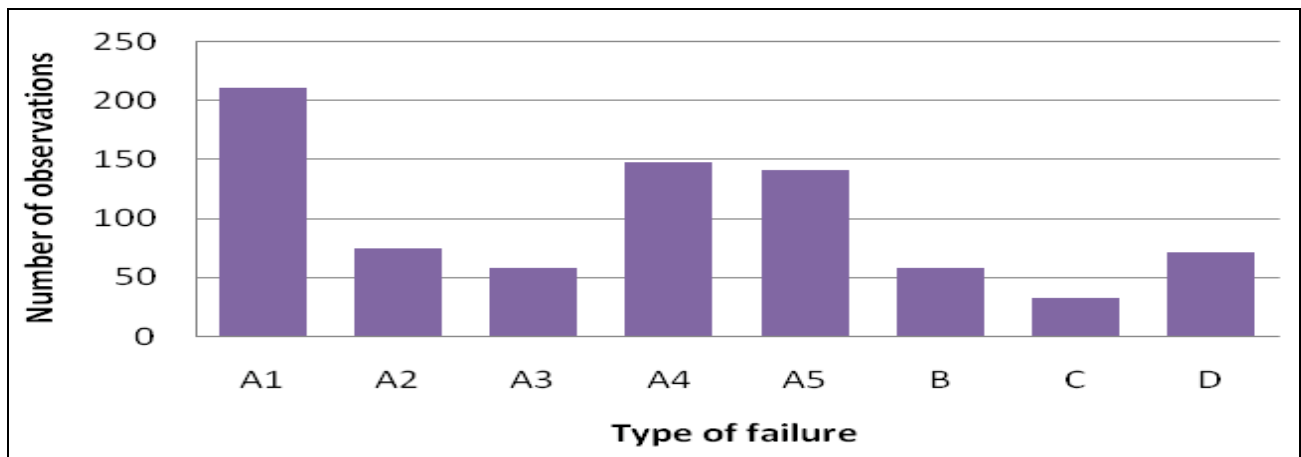


Figure A. Distribution of liquefaction related failures.

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