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# The Occurrence of Liquefaction at Low Acceleration Level

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## ABSTRACT

In common opinion, only medium-large earthquakes - i.e., those that induce peak accelerations at the ground surface equal or larger than 0.15g - are able to trigger liquefaction if susceptible soils are present. In an attempt to identify the minimum acceleration level capable to activate liquefaction phenomenon at a given site, the background data used to create some common verification charts were analysed with statistical tools. This allows detecting an acceleration threshold for the occurrence of liquefaction at around 0.1 g, value that might eventually be employed for codes and recommendations. In the light of the above considerations, in this paper, first the minimum acceleration causing pore pressure development on element tests is presented. Thereafter, a series of published case-histories of liquefaction occurrence at very low acceleration level are recalled and collected, together with new cases induced by recent earthquakes. It is then concluded that in young loose sandy deposits liquefaction might activated for peak acceleration around 0.1 g and, in some specific sites, even for lower acceleration level.

## Introduction

Major earthquakes often produce large occurrences of liquefaction. This is a phenomenon that was first rationally introduced by Mogami and Kubo (1953) and often analysed, at the present time, using the simplified Seed and Idriss (1971) approach.

Liquefaction of loose sand is one of most debated topics in Earthquake Engineering. At the moment of writing this paper, searching “liquefaction and earthquake” in the Scopus bibliographic database gives back more than 6000 documents.

Here, a literature overview of recent liquefaction cases occurred at low acceleration level is collected, to highlight the fact that liquefaction can be observed also in areas of moderate seismicity or, conversely, far from the epicentre after large earthquakes. The background idea in this research are the following: 1) the existence of a threshold acceleration for liquefaction in some codes and guidelines; 2) the occurrence of several liquefaction cases after the 2012 Emilia Earthquake in Italy, activated by a low acceleration field; and, 3) the development of a rationale procedure to define a threshold acceleration to avoid the occurrence of liquefaction, recently published by the Author and his co-workers (Santucci de Magistris el al. 2013; 2014).

## Literature Overview: The Strain Approach

Very often, the safety factor to liquefaction is provided through the ratio between the stress

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induced by the design or the given earthquake CSR and the cyclic stress resistance of the soil CRR. The latter can be expressed by means of a relationship between the cyclic stress amplitude, often normalized by the initial overburden pressure, and the number of loading cycles (i.e., Ishihara 1996 or Kramer 1996). Such laboratory curves are concave upward and are characterized often by horizontal asymptotes. For instance, the well-known laboratory test data on Monterey sand from De Alba et al. (1976), reproduced here in Figure 1, show an asymptote at a stress ratio that decreases at the reduction of the relative density. This means that there is always a cyclic stress level below which the soil's resistance to liquefaction is not exceeded, regardless of the number of loading cycles applied.

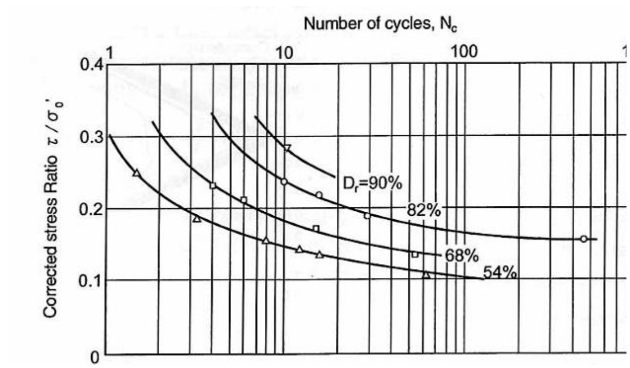



Figure 1. Cyclic stress to produce liquefaction on Monterey sand (De Alba et al., 1976)

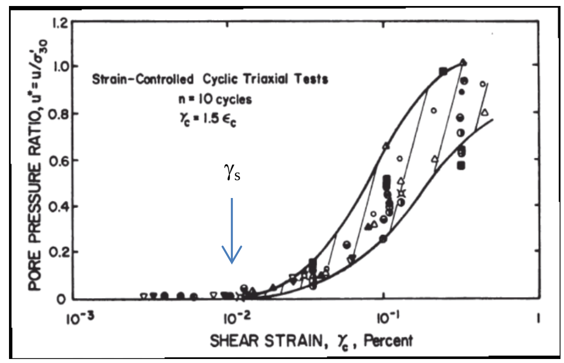



Figure 2. Pore water pressure vs. shear strain for several sands (modified after Dobry and Abdoun, 2011)

On the other hand, as recalled by Dobry and Abdoun (2011) in 5ICEGE, under cyclic loadings, there is a threshold in shear deformation $\gamma_s$ below which pore water pressure does not develop (Figure 2): pore water pressure build-up and eventual liquefaction are then necessarily associated with peak accelerations able to mobilize large deformations. Stoll and Kald (1977) proposed that the existence of this threshold deformation and its specific value around $10^{-2}$% defined a fundamental property of granular soils related to the minimum level of strain needed to start gross sliding and rearrangement of the individual particles. According to Dobry and Abdoun (2011) for "normally consolidated" sand, this threshold value is notably independent of material type, deposition method (fabric), effective confining pressure, density and prior shear straining at levels lower than the threshold. Based on the existence of $\gamma_s$, Dobry et al. (1981, 1982) estimated minimum ground surface peak acceleration, PGA, able to activate liquefaction. The threshold acceleration might be as low as 0.04 g for a site with low $G_{max}$ and shallow water table and as high as 0.20÷0.30 g for stiff overconsolidated sites with deep water table.

These statements are confirmed by the centrifuge tests of Adalier and Elgamal (2005). They measured a threshold base acceleration of about 0.04 g in the normally consolidated sand; around 0.09 g for OCR = 2 and more than 0.14 g for OCR = 4.

It can be concluded that for peak ground accelerations less than about 0.04 g no liquefaction happens, even for the worst soil conditions, i.e., shallow water table, and for large earthquake magnitudes causing the longest durations of shaking.

## Threshold Acceleration for Liquefaction in Codes and Guidelines

A threshold acceleration is indicated the new Technical Code for Construction (NTC, 2008) that is currently enforced in Italy. There, if the forecasted PGA at the ground level is below 0.1 g liquefaction is unlikely, so that specific verifications are not required. The rationale for the introduction of this threshold is discussed in Santucci de Magistris (2011). It was adopted in an attempt to comply with the Eurocode EC (EN, 2004) statements about liquefaction. There, it is indicated that the occurrence of liquefaction may be neglected when:

$$\frac{a_g}{g} \cdot S < 0.15 \qquad (1)$$

and at least one of the following conditions is fulfilled: a. the sands have a clay content greater than 20% with a plasticity index PI > 10; b. the sands have a silt content greater than 35% and an SPT blow count, normalized for overburden effects and the energy ratio, of $N_{1(60)} > 20$; and, c. the sands are clean, with an SPT blow count, normalized for overburden effects and the energy ratio, of $N_{1(60)} > 30$. In Eq. (1), $a_g$ is the design ground acceleration on type A ground, g is the acceleration of gravity and S is the soil factor (1 to 1.8) for site amplification. Therefore, EC provides a limit for the acceleration at the site surface varying between 0.15 to 0.27 g.

In NRC (1985) it is reported the existence of a typical threshold acceleration of approximately 0.1 g, although smaller accelerations associated with long-duration earthquakes may cause liquefaction in particularly susceptible soils.

Martin and Lew (1999) and CGS (2004) specified various peak ground acceleration thresholds on the basis of both soil age and groundwater level, to outline liquefaction hazard zones. In particular, hazardous areas for liquefaction might be identified where PGA was greater than 0.1 g, coupled with soils of the late Holocene age (less than 1,000 years old, current river channels and their historical flood plains, marshes, and estuaries) and groundwater less than 12 meters deep. Larger acceleration thresholds, on the order of 0.2 and 0.3 g, correspond to areas with older soils and shallower groundwater levels.

In analysing the liquefaction susceptibility in the Central San Francisco Bay Region, California, Witter et al. (2006) estimated a PGA required to trigger liquefaction greater than about 0.6 g for low susceptible deposit decreasing to 0.1 g for latest Holocene, historical stream channel, natural levee, beach deposits and artificial fill placed over San Francisco Bay mud.

Using a similar approach, Kelson et al. (2001) individuated saturated sandy alluvium associated with the present-day channel and active floodplain of the Rio Grande as deposits with high liquefaction susceptivity that may liquefy for given PGA of 0.1 g or less, given the occurrence of a magnitude 7.0 earthquake. Same for artificial fill associated with levees and embankments.

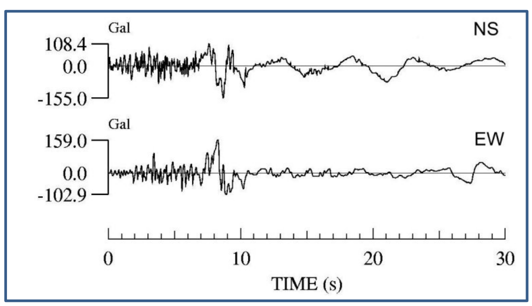
As a benchmark, it is worth remembering that the most famous example of liquefaction damages - the settling and tilting of the apartment buildings in Kawagishi-cho, Niigata because of the 1964 earthquake, Figure 3 - was due to measured peak acceleration of 0.16 g, as reported by Ishihara and Koga (1981) or Towhata (2008).

## PGA Limit Value for Simplified Liquefaction Assessment

The occurrence of several liquefaction cases in Italy after the 2012 Emilia Earthquake activated by peak acceleration below the threshold value indicated in the local building code pushed Santucci de Magistris et al. (2013, 2014) evaluating the limit acceleration by means of a critical review and validation of data collected in the technical literature. Specifically, they treacomplied a database of 201 liquefaction cases merging those used to estimate the liquefaction safety factor from simplified correlations with standard penetration tests (Boulanger et al., 2012), cone penetration tests (Moss et al., 2006), and shear wave velocity measurements (Andrus et al., 1999), following the landmark paper of Youd et al. (2001).

The data were fitted with several probability density functions. For example, using a four parameter beta function, the statistical distribution of the data is shown in Figure 4. PGAs for the lower tail areas corresponding to the first, the third and fifth percentiles are 0.090 g, 0.107 g and 0.121 g, respectively.

Employing different fitting relationships, the PGA for a cumulative probability of 1% is included in the range 0.070 ÷ 0.104 g, while at 5% is in the range 0.118 ÷ 0.138 g.




Recorded acceleration at site

Figure 3. Liquefaction in Niigata after the 1964 earthquake (www13.plala.or.jp/yasuda49/gisin/newpage1.html)

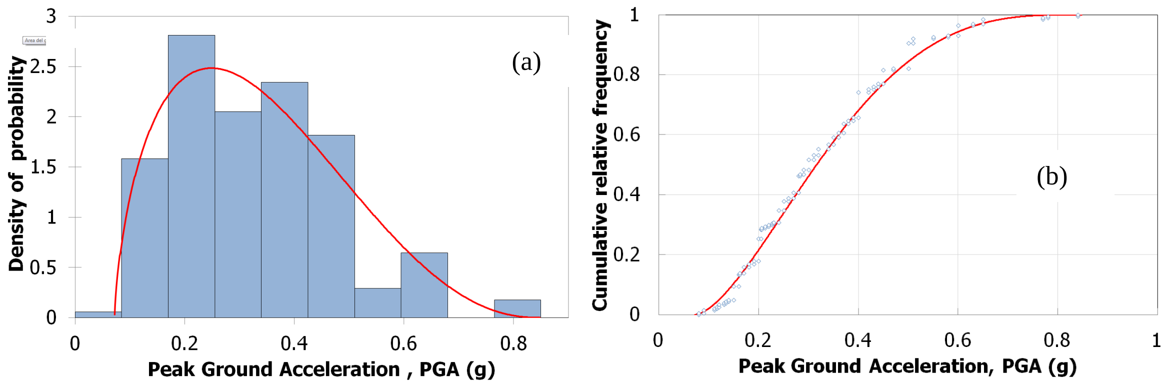



Figure 4. Maximum likelihood estimation of PGA data using a 4 parameter gamma distribution: (a) density of probability and (b) cumulative probability (Santucci de Magistris et al., 2014)

## Liquefaction at Low Acceleration Level

The threshold acceleration defined above is computed, in a rationale way, using the same dataset that is commonly employed worldwide for liquefaction analyses. However, its value is strongly influenced by the presence of case histories of liquefaction at low acceleration level. In the employed database there are seven cases of liquefaction happened at a peak acceleration lower or equal 0.12 g and three of them activated for acceleration lower than 0.10 g. In particular, during the devastating $M_w$= 7.8 1976 Tanghan, China earthquake, liquefaction was observed at the sites of Tientsin. PGA of 0.08 and 0.09 g were estimated there (Aruianandan et al., 1982), using correlation between peak acceleration, earthquake magnitude, distance from causative fault and local soil condition. However, Moss et al. (2008) underlined that the seismic loading was estimated with relatively poor initial information, since there were only six correct recordings (Huixian et al., 2002) of the earthquake.

Also, liquefaction was observed in Arayamotomachi due to the $M_w$= 7.5, 1964 Niigata earthquake. The place is located about 160 km far from the epicentre but, in this case, local peak acceleration (0.090 g) was estimated based on the PGA recorded only 4 km far from the site. In the same way, a peak acceleration of 0.111 g was attributed to the Takeda elementary school, where liquefaction happen due to an aftershock of the 1983 Nihonkai-Chubu, Japan earthquake. This acceleration was estimated based on data recorded at the Tsugaru-ohashi, about 6 km from the school (Yasuda and Tohno, 1988).

Other case histories confirmed that the threshold level should be in the order of 0.1g or less. Kuribayashi and Tatsuoka (1975) collected a series of liquefaction cases in Japan for which they estimated an acceleration level in the range of 0.080÷0.250 g. For a given site on Owi Island, Japan, the threshold acceleration for the onset of pore pressure increment was on the order of 0.06 g (Ishihara et al. 1981). Yasuda et al. (2004) have presented evidence of liquefaction for the $M_w$= 8.0 2003 Tokachi–Oki earthquake in areas where the measured PGA was equal to 0.05 g. Carr and Berrill (2004) reported a liquefaction case in Greymouth, New Zealand for which the peak acceleration due to the 1991 Hawks Crag ($M_w$= 6.2) earthquake was on the order of 0.05 g. Again in New Zealand, liquefaction occurred in Christchurch during the 2010-2011 Canterbury earthquake sequence for peak acceleration in the order of 0.08 g (Quigley et al., 2013).

An occurrence of limited liquefaction was observed in Italy after the 2009 L'Aquila earthquake (Monaco et al. 2011): the estimated PGA on the outcropping bedrock was on in the order of 0.065 g, below the limits in the Italian codes, even introducing some local soil amplification.

Kayen et al. (2004) reported about widespread liquefaction within alluvial deposits of rivers and streams in and adjacent to the central Alaska Range generated lateral-spreading cracks and sand boils as a consequence of the $M_w$= 7.9 November 2002 Denali earthquake. They also indicated the GPS coordinates where liquefaction was found. Liquefaction effects extended out from the surface rupture for approximately 100–120 km. Using ShakeMaps (Wald et al., 2006) it appears that the phenomenon in several sites was activated by estimated PGA of 0.11÷0.13 g and, in some sites, for peak acceleration lower than 0.1 g. Liquefaction at the lowest acceleration (around 0.08 g) was found along Tanana River, where fluvial deposits of sand and silt were capped by a thin frozen surface layer.

Another set of liquefaction cases activated under low acceleration fields was found after the great Mw= 7.9 2008 Wenchuan, China earthquake provoking a number of causalities as large as 70000. Chen et al. (2009) reported cases of liquefaction and serious related damage at more than ten sites where the seismic intensity was VI. This shows that areas with moderate seismic intensity can also liquefy as a result of relatively high-amplitude ground motion and a sufficient duration of shaking. Geographic coordinates of the sites were liquefaction occurred were manually obtained using their published map and compared with the data of the USGS ShakeMap for the event. It can be noticed that liquefaction was activated, in some cases, for peak accelerations lower than 0.1 g, and even for PGA not larger than 0.055 g.

A liquefaction case at low acceleration level was reported by Verdugo (2012) as a consequence of the huge February 2010, off the coast of Maule, Chile earthquake ($M_w$ 8.8). Liquefied sites were observed in areas where the intensity was less than V.

Specifically, lateral spreading and liquefaction were noticed in banks of Lake Calafquén along the route Coñaripe - Lican Ray. According to Verdugo (2012) this necessarily implies that the intensity of the quake, which correlates directly with structural damages, is not completely associated with the occurrence of liquefaction. Although this confirms the well-known dependence of the liquefaction strength on both level of cyclic stresses and number of cycles, it also shows the actual impact of the earthquake duration on the liquefaction strength. Again, by comparing the site coordinate and the USGS ShakeMap it appears that liquefaction was activated for PGA in the order of 0.09 g.

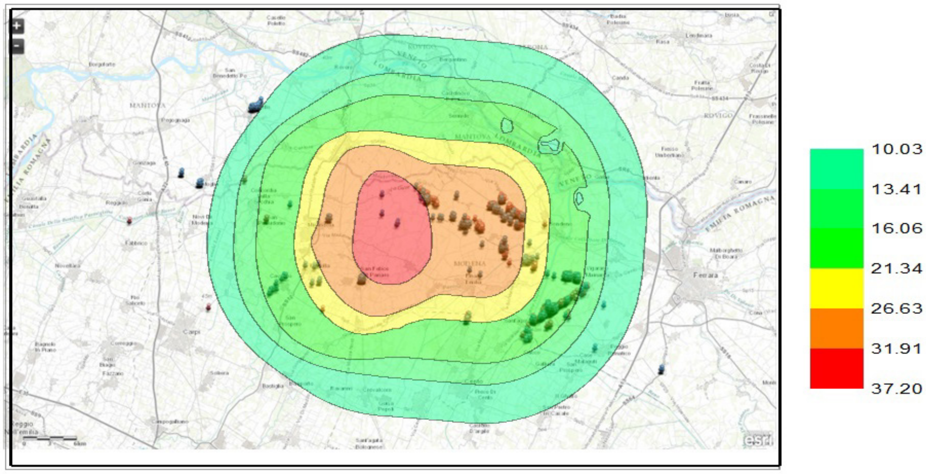



Figure 5. Liquefaction sites due to the 2012 Emilia earthquake and PGA contour (%/g) after INGV ShakeMap

In discussing about the liquefaction occurred after the 2011 off the Pacific coast of Tohoku earthquake, Wakamatsu (2012) highlighted that the farthest liquefied site was in Minami-boso City on the Boso Peninsula where the epicentral distance was 440 km. Again using the ShakeMap it appears that the peak acceleration at the site was around 0.095 g. In analyzing the ground motion, Hata et al. (2013) sustained that the number of cycles included in the input ground motions played an important role in the occurrence of liquefaction at the target site. They also added that site-specific feature of strong ground motions was one of the main causes of the occurrence of liquefaction 440 km away from the epicentre; while it is important to take into account not only soil properties but also site-specific characteristics of strong ground motions for a rational assessment of liquefaction for future large earthquakes.

Finally, referring to the 2012 Emilia earthquake, Italy, Figure 5 shows a map of liquefaction sites overlapped with a PGA ShakeMap. In the farthest site from the epicentre liquefaction was triggered by ground-level horizontal peak acceleration of approximately 0.08 g. The coordinates of the liquefaction sites were provided by Emergeo Working Group (2013) while the peak acceleration map is that provided by ShakeMap prepared by both USGS and the Italian INGV.

## Conclusions

This paper collects a series of liquefaction case-histories that were activated in sites where the estimated peak ground acceleration at surface is limited. The existence of such cases supported the existence of a relatively low threshold of peak acceleration for the triggering of the phenomenon, in very prone areas, in the order of 0.1 g. A similar threshold was already proposed by Dobry and co-workers through the so called "strain method" and by Santucci de Magistris and co-workers, exploiting the data employed in the analysis charts for liquefaction.

The search of case-histories was made gathering already published papers and checking the evidence of liquefaction in recent post-event reports such as those of the GEER association (www.geerassociation.org). For each reported case, the surface PGA was estimated using ShakeMaps and data are reported here if liquefaction was activated by low acceleration level.

For the reported case, while occurrence and location of the phenomena are well reliable, the correct estimation of the local PGA as obtained by ShakeMaps is sometime questionable and could represent a limit in the reported results. Also, not always information on the local geological and geotechnical conditions is provided. Rarely, acceleration time histories close to sites liquefied for low acceleration level are available, to check if the activation of the phenomenon is noteworthy due to a large number of cycles. This seems however not always the case, since in some occurrences the triggering earthquake was moderate in magnitude.

In spite of this limitation, the relative high numbers of collected cases confirm the background idea that liquefaction might be activated, in some specific sites, even for modest peak acceleration on soil surface.

## References

Adalier K, Elgamal A. Liquefaction of over-consolidated sand: a centrifuge investigation. *J. Earthq. Eng*. 2005; **9**(SI1): 127–150.

Andrus RD, Stokoe KH II, Chung RM. *Draft guidelines for evaluating liquefaction resistance using shear wave velocity measurements and simplified procedures*. NISTIR 6277, 1999.

Arulanandan K., Douglas BJ, Qu YZ, Junfei X, Chengchun W, Qizhi H. Evaluation of earthquake induced liquefaction in Tientsin during the Tangshan Earthquake PRC. *Proc. US-PRC Bilateral Workshop on Earthq Eng*, 1982; E-3-1–E-3-42.

Boulanger RW, Wilson DW, Idriss IM. Examination and Reevaluation of SPT-Based Liquefaction Triggering Case Histories. *J. of Geotech. and Geoenviron. Eng*. ASCE 2012; **138**(8):898-909.

Carr K, Berrill J. Liquefaction case histories from the West Coast of the South Island, New Zealand. *13th WCEE*, Vancouver, B.C., Canada 2004; Paper No. 1325.

Chen L, Hou L, Cao Z, Yuan X, Sun R, Wang W, Mang F, Chen H, Dong L. Liquefaction investigation of Wenchuan earthquake. *Proc. 14th WCEE*, 2008, Beijing, China.

C.G.S. Recommended criteria for delineating seismic hazard zones in California. *SP 118*, CGS, 2004.

De Alba P, Seed HB, Chan CK. Sand liquefaction in large-scale simple shear tests. *J. Soil Mech. Found. Div*., ASCE 1976;**102**(9): 909–927.

Dobry R, Yokel FY, Ladd RS. Liquefaction Potential of Overconsolidated Sands in Areas with Moderate *Seismicity. Earthq. and Earthq. Eng.: The Eastern U.S.* (J.E. Beavers, ed.) 1981; **2**:642-664.

Dobry R, Ladd RS, Yokel FY, Chung RM, Powell D. Prediction of Pore Water Pressure Buildup and Liquefaction of Sands during Earthquakes by the Cyclic Strain Method. *NBS Build. Sci.* Ser. **138**, 1982.

Dobry R, Abdoun T. An investigation into why liquefaction charts work: a necessary step toward integrating the states of art and practice. *Proc. 5ICEGE* Santiago, Chile 2011; 13-45.

Emergeo Working Group. Liquefaction phenomena associated with the Emilia earthquake sequence of May–June 2012 (Northern Italy). *Nat. Hazards Earth Syst. Sci*., 2013; **13**:935–947.

Eurocode 8 EN 1998-5, *design of structures for earthquake resistance—part 5: foundations, retaining structures and geotechnical aspects*. CEN European Committee for Standardization, Bruxelles, Belgium, 2004.

Hata Y, Ichii K, Nozu A, Maruyama Y, Sakai H. Ground motion estimation at the farthest liquefaction site during the 2011off the Pacific coast of Tohoku earthquake. *Soil Dyn. Eq. Eng*. 2013; **48**:132–142.

Huixian L, Housner G W, Lili X, Duxin H. *The Great Tangshan Earthquake of 1976*. EERL, CalTech, 2002.

Ishihara K. *Soil behaviour in earthquake geotechnics*. Oxford Un. Press: Oxford, UK, 1996.

Ishihara K, Koga Y. Case studies of liquefaction in the 1964 Niigata earthquake. *Soils Fndn.*, 1981; **21**(3): 35-52.

Ishihara K, Shimizu K, Yamada Y. Pore water pressures measured in sand deposits during an earthquake. *Soils Fndn.*, 1981; **21**(4):85-100.

Kelson KI, Hitchcock CS, Randolph CE. *Surface geology and liquefaction susceptibility in the inner Rio Grande valley near Albuquerque*, New Mexico. NMBGMR OFR454-D, 2001.

Kayen R, Thompson E, Minasian D, Moss RES, Collins BD, Sitar N, Dreger D, Carverc G. Geotechnical Reconnaissance of the 2002 Denali Fault, Alaska, Earthquake. *Eq. Spectra*, 2004; **20**(3). 639–667.

Kramer SL. *Geotechnical Earthquake Engineering.* Prentice Hall, 1996.

Kuribayashi E, Tatsuoka F. Brief review of liquefaction during earthquakes in Japan. *Soils Fndn*., 1975; **154**:81-92.

Martin GR, Lew M. Recommended Procedures for Implementation of DMG. SP 117*: Guidelines for Analyzing and Mitigating Liquefaction Hazards in California*, SCEC, University of Southern California, 1999.

Mogami T, Kubo K. The behavior of soil during vibration. *Proc. 3rd ICSMFE* 1953; **1**: 152-155.

Monaco P, Santucci de Magistris F, Grasso S, Marchetti S, Maugeri M, Totani G. Analysis of the liquefaction phenomena in the village of Vittorito (L'Aquila). *Bull. Earthq. Eng*., 2011; **9**:231–261.

Moss RES, Seed RB, Kayen RE, Stewart JP, Der Kiureghian A, Cetin KO. CPT-Based Probabilistic and Deterministic Assessment of In Situ Seismic Soil Liquefaction Potential. *J. of Geotech. and Geoenviron. Eng.* ASCE, 2006; **132**(8):1032–1051.

Moss RES, Kayen RE, Liu S, Tong L, Du G, Cai G, Cao Z, Lijing S. Re-investigating Liquefaction Case Histories from the 1976 Tangshan Earthquake. *Proc. 14$^{th}$ WCEE*, 2008, Beijing, China.

N.R.C. *Liquefaction of soils during earthquakes*. Committee on Earthquake Engineering, NRC U.S, 1985.

N.T.C. Approvazione delle nuove norme tecniche per le costruzioni (Italian Building Code). *Gazzetta Ufficiale della Repubblica Italiana*, n. 29 del 4 febbraio 2008 – Suppl. Ordinario n. 30, 2008 (in Italian).

Quigley MC, Bastin S, Bradley BA. Recurrent liquefaction in Christchurch, New Zealand, during the Canterbury earthquake sequence. *Geology*, 2013; **41**: 419–422.

Santucci de Magistris F. Beyond EC8: the New Italian Seismic Code. *Geofizika*, 2011;**28**, 65-82.

Santucci de Magistris F, Lanzano G, Forte G, Fabbrocino G. A database for PGA threshold in liquefaction occurrence. *Soil Dynamics and Earthquake Engineering* 2013; **54**:17-19.

Santucci de Magistris F, Lanzano G, Forte G, Fabbrocino G. A peak acceleration threshold for soil liquefaction: lessons learned from the 2012 Emilia earthquake (Italy). *Natural Hazards* 2014; **74**(2): 1069-1094.

Seed HB, Idriss IM. Simplified procedure for evaluating soil liquefaction potential, *J. Soil Mech. and Found. Div*. 1971; **97**(9): 1249–1273.

Stoll RD, Kald L. Threshold of Dilation under Cyclic Loading. *J. Geot. Eng. Div*. ASCE 1977,**103**(10) 1174-1178.

Towhata I. *Geotechnical Earthquake Engineering*. Springer Series in Geomechanics and Geoengineering, 2010.

Verdugo R. Comparing liquefaction phenomena observed during the 2010 Maule, Chile earthquake and 2011 Great East Japan earthquake. *Proc. Int. Symp. on Eng. Lessons Lrn. from the 2011 Great East J. Eq*., 2012; Tokyo.

Wakamatsu K. Recurrent liquefaction induced by the 2011 Great East Japan earthquake compared with the 1987 earthquake. *Proc. Int. Symp. on Eng. Lessons Lrn. from the 2011 Great East J. Eq.*, 2012; Tokyo.

Wald DJ, Worden CB, Quitoriano V, Pankow KL. *ShakeMap® Manual.* Technical Manual, Users Guide, and Software Guide. ANSS, 2006.

Witter RC, Knudsen KL, Sowers JM, Wentworth CM, Koehler RD, Randolph CE. *Maps of Quaternary Deposits* *and Liquefaction Susceptibility in the Central San Francisco Bay Region*, California. U.S.G.S. Open-File Report 2006-1037; 2006.

Yasuda S, Tohno I. Sites of Reliquefaction Caused by the Nihonkai-Chubu Earthq. *Soils Fond*, 1988; **28**(2): 61-72.

Yasuda S, Morimoto I, Kiku H, Tanaka T. Reconnaissance report on the damage caused by three Japanese earthquakes in 2003. *Proc. 11$^{th}$ ICSDEE and 3$^{rd}$ ICEGE*, Doolin, D. et al. Ed., Berkeley, CA, 2004; 1: 14–21.

Youd TL et al. Liquefaction resistance of soils: summary report from the 1996 NCEER and 1998 NCEER/NSF workshops on evaluation of liquefaction resistance of soils. *J. of Geotech. and Geoenviron. Eng*. ASCE, 2001; **127**(10): 817-833.