Attenuation of Seismic Wave Energy and Liquefaction Limit during the Great Wenchuan Earthquake

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SUMMARY:
The present study identified and compiled a large amount of liquefaction case histories from the great Wenchuan earthquake occurred in May 12, 2008, P. R. China, to highlight the relationship between the attenuation of seismic wave energy and liquefaction limit during this earthquake. Firstly, the earthquake magnitude-energy-distance relationship was derived based on the strong motion observations of this event, and the liquefaction limit for the main shock is estimated according to typical energy demand to induce liquefaction. Then the liquefaction case histories obtained from site investigations are used to verify such estimation, and the threshold seismic energy to cause liquefaction occurrence in this area is back analyzed and the possible mechanisms are discussed. This study provides the verification for energy-based liquefaction assessment on a broader scale and could be applied to set limits to the expected extent of liquefaction when the detailed data of sediment properties and subsurface structures of the area of interest are not available. The present study may be considered as a promising tool in evaluating the liquefaction risk of typical soil deposits in Chengdu Plain, Sichuan Province during potential earthquakes.

Keywords: Liquefaction; Seismic wave energy; Attenuation; Wenchuan Earthquake

1. INSTRUCTION

Large earthquakes often cause saturated soils to liquefaction, which is a major source of seismic hazard (Seed and Lee 1966). Soil liquefaction describes a phenomenon whereby a saturated soil substantially loses strength and stiffness in response to earthquake shaking, causing it to behave like liquid. Field and laboratory studies show that the occurrence of liquefaction depends on many factors and empirical approaches are usually adopted as a rule in assessing the liquefaction potential of an area (Youd et al. 2001; Juang et al. 2002; Zhou and Chen 2007; Zhou et al. 2010). Field observations show that, for earthquakes of a given magnitude M, the occurrence of liquefaction is confined within a particular distance from the earthquake focus, beyond which liquefaction may not be expected (Galli 2000; Ambraseys 1988). Thus the application of the liquefaction limit to an area without prior information on its liquefaction susceptibility may only be taken as an estimation of the maximum likelihood of liquefaction occurrence during a potential earthquake. Such estimation will be very valuable for emergency responses and reconnaissance efforts shortly after the occurrence of a big earthquake.

At 06:28:01 UTC on May 12, 2008 (14:28:01, Beijing time), a devastating earthquake occurred at Wenchuan County in Sichuan Province of China. The earthquake was of M_w = 7.9 according to the United States Geological Survey (USGS) and M_s = 8.0 according to the China Earthquake Administration (CEA). The epicentre (at latitude 31.021°N, longitude 103.367°E) of the earthquake was 80 km west-northwest of Chengdu. The fault ruptured at a depth of about 19 km. The highest intensity level recorded from the earthquake was XI (Tsang 2008). Because gravelly and sandy soil layers widely spread in the Chengdu Plain, wide spreading liquefaction occurrences were reported from various sources (e.g., Chen et al. 2009; Yuan et al. 2009; Zhou et al. 2009). Figure 1 presents typical photos of liquefaction identified shortly after the earthquake.

(a)

(b)

Figure 1. Typical sand ejections in west part of Chendu Plain: (a) Deyang site (from Prof. E. D. Guo); (b) Pixian site (from Prof. Z. F. Wang)

The present study compiled a large amount of liquefaction case history data in the great Wenchuan earthquake, to highlight the relationship between liquefaction risk and seismic energy demand. The liquefaction risks for the M_w = 7.9 main shock is estimated according to typical energy demand to induce liquefaction. The proposed relationship and threshold seismic energy value may be considered as a tool in evaluating the minimum energy of an earthquake that induced liquefaction in this area, and may be applied to set some limits to the expected extent of liquefaction during potential earthquakes, when the detailed information of the area are not available.

2. ESTIMATION OF LIQUEFACTION ZONE

As seismic waves propagate through soil, a portion of their energy dissipates, resulting a reduction in the amplitude of the waves (i.e., attenuation) and soil liquefaction if the dissipated energy is large enough. The procedure estimating the liquefaction onset for a specific site based on seismic energy concept requires two major parameters: the first is the energy Demand, which is the energy imparted to the soil by earthquake; the second is the energy Capacity, which is the Demand required to induce liquefaction at the site, and usually defined as the cumulative energy dissipated up to the point of liquefaction. Then the factor of safety of liquefaction is defined as the ratio of Capacity and Demand.

As for the energy Demand, it is dominated by the attenuation of ground motion and could be derived approximately by the earthquake magnitude-energy-distance relationship for a given earthquake. The present study adopts the following empirical derivations mainly from Wang et al. (2006) and Wang (2007), in consideration of its simplicity and effectiveness. As for the energy Capacity, it is presented in terms of the accumulative absorbed mechanical energy, and could be computed by integrating the stress-strain hysteretic loops up to initial liquefaction in laboratory and in the field. Therefore it is essentially the "accumulative" damping during the liquefaction process.

Once the attenuation relationship of seismic wave energy and threshold energy for liquefaction triggering are determined, the liquefaction limit of a given earthquake could be readily estimated. The following sections are presented to address these problems.

2.1. Earthquake magnitude-energy-distance relationship

According to Wang et al. (2006), the liquefaction limit R_{max} is interpreted as the distance at which the seismic energy density $e(r)$ has decayed to a threshold energy density e_{th} required to trigger liquefaction under the most favourable condition (i.e., saturated soils with high liquefaction susceptibility), then the form for the attenuation of ground motion energy density with distance is assumed as following:

$$e(r) = \frac{E_{eq}}{(r+1)^{\alpha}} \tag{2.1}$$

where r is the distance from the earthquake source in kilometres, E_{eq} stands for the total seismic energy of the earthquake; α is an empirical constant ranging from 3 to 3.3; and the term "+1" is included so that the seismic energy in a unit volume at r =0.

Since most energy in the ground motion resides in the peak ground velocity, and the cumulative ground-motion energy like e_{Ar} of Arias intensity for horizontal S waves is closely proportional to the square of PGV (Jennings 2003), Wang et al. (2006) proposed that $e(r)$ is proportional to $(PGV)^2$. On the other hand, Cua (2004) showed that the amplitude of the horizontal S-wave velocity envelope declines with distance according to $1/r^{1.59}$ at soil sites. This follows that $e(r)$ is approximately proportional to $1/r^3$ in statistic level.

To relate R_{max} to the seismic-wave energy of an earthquake E_{eq}, this study uses the widely known relation between E_{eq} and M proposed by Bath (1966):

$$\log E_{eq} = 5.24 + 1.44M \tag{2.2}$$

Combining Equations (2.1) with (2.2), the following equation can be obtained:

$$M = 2.61 + 0.694 \log e + 2.08 \log r \tag{2.3}$$

Equation (2.3) implies that at a given earthquake magnitude, R_{max} could be estimated for liquefiable sediments, as long as the threshold energy density e_{th} required for a given type of soil is specified and the ratio of dissipated and imparted energy in different types of liquefiable soil are given. Because ground motion parameters or hazard information could not be available shortly after the occurrence of an earthquake with a given magnitude, this equation could provide the approximate estimation of liquefaction possibility at different distances to the hypocenter, namely, rapid prediction of the liquefaction risk during an earthquake.

2.2. Threshold energy and liquefaction limit estimation

From the analysis of earthquake case histories, Green and Mitchell (2004) developed a correlation relating the dissipated energy per unit volume required to induce liquefaction. Using this correlation, the dissipated energy required to induce liquefaction (e.g., the threshold energy density e_{th}) in a soil confined at an effective pressure of 100 kPa ranges from 30 to 192 J/m^3. Herein this study adopted the lower and upper value of e_{th} and the assumed average material damping during liquefaction of sandy soils to estimate the liquefaction limit distance R_{max}. As for average damping ratio, ξ = 10%, 20% and 100% are assumed for extreme condition estimation. Therefore, when e_{th} =30 J/m^3, the threshold imparted energy ($e_{th\text{-}imp}$) required for liquefaction triggering will be 300 J/m^3 for an average damping ratio of 10%.

Table 2.1 lists the calculation result by Equation (2.3) with the e_{th} values mentioned above. For the great Wenchuan earthquake, the liquefaction limit R_{max} may be 52.1 km, which is obviously within the near field of this earthquake.

Table 2.1. R_{max} estimation during the great Wenchuan earthquake (M_w = 7.9)

$e_{th\text{-}dis}$ (J/m^3)	Lower: 30 (J/m^3)			Upper: 192 (J/m^3)		
Average damping (%)	10	20	100	10	20	100
$e_{th\text{-}imp}$ (J/m^3)	300	150	30	1920	960	192
R_{max} (km)	52.1	65.6	112.3	28.0	35.3	60.5

3. VERIFICATION BY SITE INVESTIGATIONS

3.1. Earthquake magnitude-energy-distance relationship

A great effort has been made by many researchers following the great Wenchuan earthquake. Through months of reconnaissance work and field investigations, 120 liquefied sites were identified (Zhou et al. 2009). These cases are plotted in Figure 1 together with 14 datasets from other researchers (e.g., Yuan et al. 2009; Wang et al. 2009). In this database, the occurrences of liquefaction were identified by obvious sand boils, accompanying by other features like ground fissure, crack or settlement of building foundations in the field. As shown in Figure 2, most of the identified liquefied sites locate in the west part of Chengdu Plain and Mianyang area along with the fault rupture, and about 90% of them falls into the zone with MMI scale no less than VII, which envelopes a rectangular area about 300 km long and 125 km wide. This implies that the style of faulting and directivity of an earthquake will influence the liquefaction distribution profoundly.

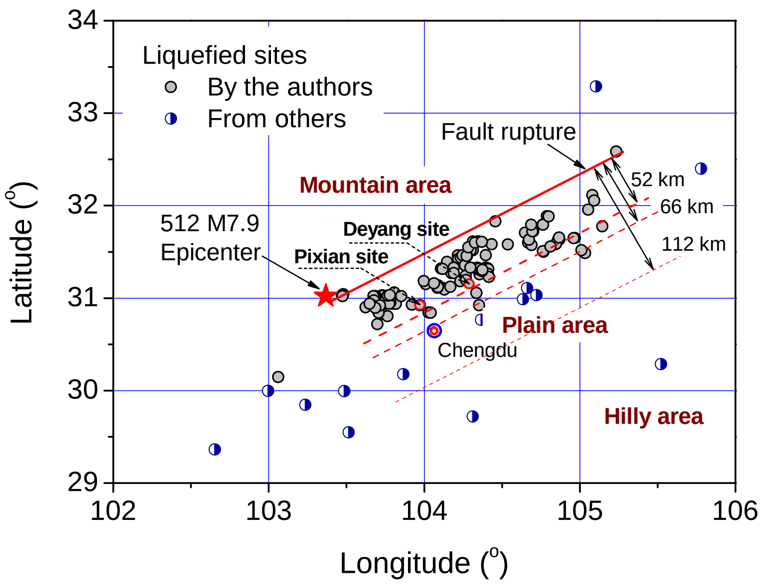

Figure 2. Liquefaction sites identified in the great Wenchuan earthquake

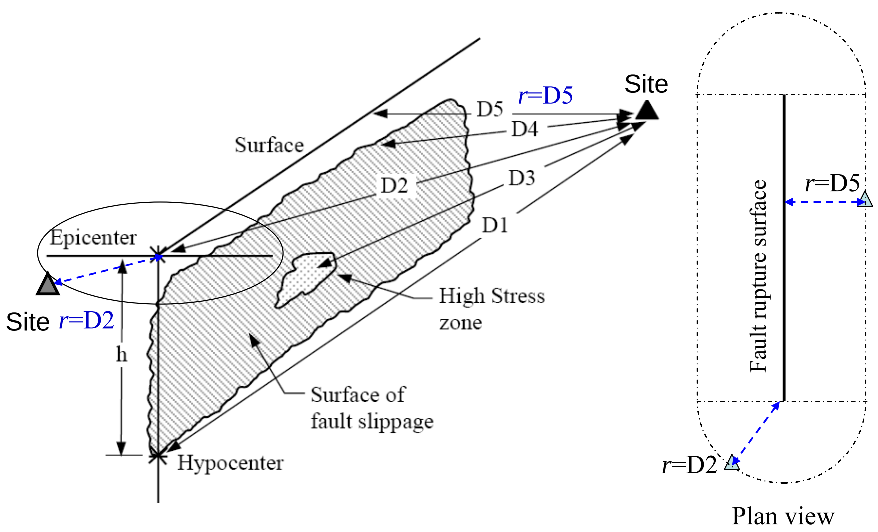

Figure 3. Site-to-source distance (modified from Green 2001)

In consideration of the focal mechanism solution, D1 and D2 in Figure 3 are adopted as the hypocentral (D_{hyp}) and epicentral (D_{epi}) distances respectively. And D5, the closest distance to the surface projection of rupture plane in kilometres, is adopted as D_{rup} for comparison purpose. Note that for the linear type of fault rupture, the identification of D_{rup} is illustrated in Figure 3. Based on the database in Figure 2, the observed R_{max} value of the $M_w = 7.9$ main shock is approximately 298.6 km and 298.0 km for D_{hyp} and D_{epi} respectively, while $R_{max} = D_{rup} = 197.7$ km.

The distribution characteristics of number of liquefaction cases in terms of different definition of r (i.e., r=D1 and D5) are plotted in Figures 4 and 5. As shown in Figure 4, the distribution of number of liquefied cases with $r = D_{rup}$ clearly reflects the common decaying trend, while in Figure 5 the one with $r = D_{epi}$ shows much more arbitrary. This follows that for linear type of fault rupture, the definition of D5 could reasonably represent r for developing the earthquake magnitude-liquefaction distance relationship. Besides, most of the liquefaction cases concentrated in the zone with D_{rup} less than 52.1 km, which strongly implies that the assumed 10% average damping ratio is generally appropriate for most liquefaction cases.

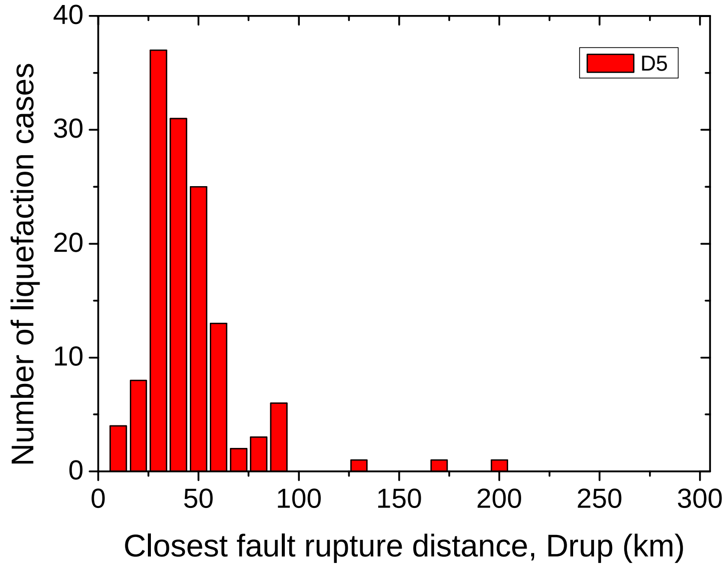

Figure 4. Number of liquefaction cases with D_{rup}(=D5)

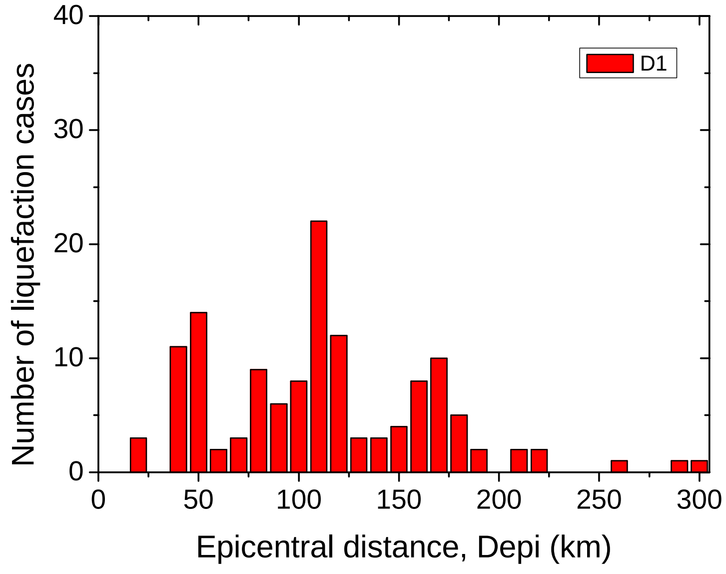

Figure 5. Number of liquefaction cases with D_{hyp}(=D1)

3.2. Back analysis of threshold seismic energy e_{th}

Figure 6 shows a recent compilation of global data for liquefaction, in which the hypocenter distance *R* of the documented liquefaction site is plotted against earthquake magnitude *M* (Wang 2007). The two R_{max} (= D_{hyp} and D_{rup}) values for $M_w = 7.9$ during the great Wenchuan earthquake are plotted in Figure 6. As shown in Figure 6, the liquefaction limit based on hypocentral distance almost falls on the e =1 J/m^3 estimation line, while the value based on closest distance is about e =3 J/m^3 line. Both of them are far beyond the dissipated threshold energy e_{th} = 30 J/m^3 which is for the extreme case that all imported seismic energy is dissipated by soil (i.e., damping is 100%). Such results imply that real liquefaction occurrence in this earthquake is much further than the limit derived from soil element tests or in-situ penetration tests.

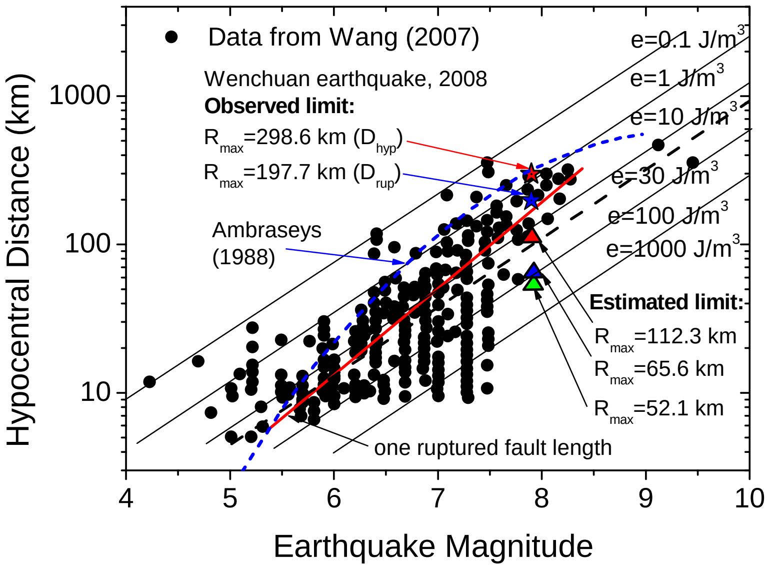

Figure 6. Global dataset of documented liquefaction (adapted from Wang 2007)

There are several possible reasons might explain such features in Figure 6. The first one might result from the engineering geological characteristics of the affected area. The west part of Chengdu Plain overlies deep gravelly-sandy soil deposits and suffered serious liquefaction, while the east part gradually merges into hilly areas, where the liquefaction susceptibility of sediments decreases generally. However, in some valley or basin structure units with rivers across them, the strong local site effects caused liquefaction occurrence in loose alluvial deposits beyond the near field. This kind of liquefaction could still be with energy dissipation close to the level of e_{th} = 30 J/m^3, although the site effect and highly scarce distribution mask this fact and makes the "average" e_{th} approach to 1-3 J/m^3. Thus e_{th} = 3 J/m^3 might be taken as the "apparent" threshold seismic energy to cause liquefaction for Chengdu Plain during potential big earthquakes, in consideration of the complex attenuation characteristics of ground motion and site effects.

4. CONCLUSIONS

The present study identified and compiled a large amount of liquefaction case history data from the great Wenchuan earthquake occurred in May 12, 2008, P. R. China. The liquefaction limit was estimated according to typical energy demand to induce liquefaction. This study indicates that the dissipated energy threshold e_{th} = 30 J/m^3 still holds true, while in consideration of the complex ground motion, geological, water and sediment conditions, e_{th} = 3 J/m^3 is preliminarily proposed as the "apparent" dissipated threshold energy to cause liquefaction for Chengdu Plain during potential big earthquakes. In consideration of the fact that the energy attenuation relationship might be quantitatively different from Eq. (2.1) for the great Wenchuan Earthquake, the earthquake specific parameter should be back analyzed to improve the accuracy of threshold energy prediction for this earthquake. This study provides the verification for energy-based liquefaction assessment on a broader scale, and may be applied to estimate the maximum likelihood of liquefaction occurrence in typical soil deposits in Chengdu Plain, especially at the emergent response stages of potential big earthquakes.

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REFERENCES

Ambraseys, N.N. (1988). Engineering seismology. *International Journal Earthquake Engineering Structural. Dynamics* **17**, 1-105

Bath, M. (1966). Earthquake energy and magnitude. *Physics and chemistry of the Earth* **7**, 115-165.

Chen, L.W., Yuan, X.M., Cao, Z.Z. et al. (2009). Liquefaction macrophenomena in the great Wenchuan earthquake. *Earthquake Engineering and Engineering Vibration* **8:2**, 216-229.

Galli, P. (2000). New empirical relationships between magnitude and distance for liquefaction. *Tectonophysics* **324**,169-187.

Green, R.A. (2001). Energy-based evaluation and remediation of liquefiable soils. PhD Thesis, Dept. of Civil Engineering, Virginia Polytechnic Institute and State University, 393p.

Green, R.A. and Mitchell J.K. (2004). Energy-based evaluation and remediation of liquefiable soils. Geotechnical Engineering for Transportation Projects, eds. Yegian M. and Kavazanjian E., GSP No. 126, ASCE: 1961-1970.

Jennings, P.C. (2003). An introduction to the earthquake response of structures. in International Handbook of Earthquake and Engineering Seismology, Part B, Academic Press, Amsterdam: 1097-1125.

Juang, C.H., Jiang, T. and Andrus, R.D. (2002). Assessing probabilitybased methods for liquefaction potential evaluation. *Journal of Geotechnical and Geoenvironmental Engineering ASCE* **128:7**, 580-589.

Liu, Q.F. and Li, X.J. (2009). Preliminary analysis of the hanging wall effect and velocity pulse of the 5.12 Wenchuan earthquake. *Earthquake Engineering and Engineering Vibration* **8:2**, 165-177.

Seed, H. B. and K. L. Lee (1966). Liquefaction of saturated sands during cyclic loading. *Journal of the Soil Mechanics and Foundation Division ASCE* **92:6**, 105-134.

Tsang, H.H. (2008). Lessons learnt from the 512 Wenchuan earthquake: perception of seismic risks. Australian Earthq. Engrg. Society Conference AEES 2008, Ballarat, Victoria: 1-16.

Wang, C.Y. (2007). Liquefaction beyond the Near Field. *Seismological Research Letters* **78:5**, 512-517.

Wang, C.Y., Wong A., Dreger, D.S. and Manga M. (2006). Liquefaction limit during earthquakes and underground explosions: implications on ground-motion attenuation. *Bulletin of the Seismological Society of America* **96:1**, 355-363.

Wang, L.M., Wu, Z.J. and Sun, J.J. (2009). Characteristics of disasters induced by the Wenchuan 8.0 earthquake and its lessons. Earthquakes and Tsunamis: Civil Engineering Disaster Mitigation Activities Implementing Millennium Development Goals. Tankut, A. Tugrul (editor), Springer: 179-208.

Youd, T.L., Idriss, I.M., Andrus, R.D. et al. (2001). Liquefaction resistance of soils: Summary report from the 1996 NCEER and 1998 NCEER/NSF workshops on evaluation of liquefaction resistance of soils. *Journal of Geotechnical and Geoenvironmental Engineering ASCE* **127:10**, 817-833.

Yuan, X.M., Cao, Z.Z., Sun, R. et al. (2009). Preliminary Research on Liquefaction Characteristics of Wenchuan 8.0 Earthquake. *Chinese Journal of Rock Mechanics and Engineering* **28:6**, 1288-1296. (in Chinese).

Zhou, Y.G. and Chen, Y.M. (2007). Laboratory investigation on assessing liquefaction resistance of sandy soils by shear wave velocity. *Journal of Geotechnical and Geoenvironmental Engineering ASCE* **133:8**, 959-972.

Zhou, Y.G., Chen, Y.M. and Ling, D.S. (2009). Shear wave velocity-based liquefaction evaluation in the great Wenchuan earthquake: a preliminary case study. *Earthquake Engineering and Engineering Vibration* **8:2**, 230-239.

Zhou, Y. G., Chen, Y. M. and Shamoto Y. (2010). Verification of the soil-type specific correlation between liquefaction resistance and shear-wave velocity of sand by dynamic centrifuge test. *Journal of Geotechnical and Geoenvironmental Engineering ASCE* **136:1**, 165-177.