Laboratory Liquefaction Test of Sand Based on Grain Size and Relative Density

Abdul Hakam

Civil Engineering Department, Engineering Faculty of Andalas University
Kampus Unand Limau Manis, Padang 25136, Indonesia
E-mail: ahakam@ft.unand.ac.id

Abstract. Liquefaction due to strong earthquakes often occurs in sandy soil under low water table conditions with certain physical properties. The physical properties of sandy soil that give effect to liquefaction resistance include grain size and relative density. This paper presents the physical properties of sand soils related to their resistance to vibration. Vibration tests were conducted by using a shaking table. The acceleration and settlement of the samples were recorded during shaking. The tests were conducted with variation of soil density and mean grain size. The test results showed that average grain size and relative density of sand have a unique effect on liquefaction resistance. It can be concluded that there is a density limit with respect to the mean grain size of the sand particles associated with the liquefaction resistance for a certain acceleration.

Keywords: *earthquake; laboratory test; liquefaction; relative density; soil particle size.*

1 Introduction

The assessment of liquefaction potential is a challenging research area because of the inherent unknowns associated with uncertainties in earthquakes. Thus, it is important to use a simple analysis to get a good estimation of liquefaction problems. It has been summarized that newly deposited loose sands under shallow ground water are susceptible to liquefaction [1]. There are a number of different ways to evaluate the liquefaction susceptibility of soil deposits, as summarized by Kramer [2]. The first one uses the liquefaction history, where soils that were liquefied in the past could be liquefied again in a future earthquake. Then there is the geological process that sorts particles into uniform grain sizes in loose sand conditions. The liquefaction susceptibility also depends on soil type, where fine-size particles are more susceptible to liquefaction than coarse particles. Other important factors are soil density and effective stress at the time the soil is subjected to shaking. Loose soils are easier to liquefy than dense soils under the same effective stress. At the same density, soils under high effective stress are easier to liquefy than soils under low effective stress.

Received January 20th, 2015, 1st Revision June 16th, 2015, 2nd Revision July 7th, 2015, 3rd Revision September 15th, 2015, 4th Revision March 8th, 2016, 5th Revision June 7th, 2016, 6th Revision July 12th, 2016, Accepted for publication July 29th, 2016.
 ISSN: 2337-5779, DOI: 10.5614/j.eng.technol.sci.2016.48.3.7

The assessment of the liquefaction potential of soil deposits has been an important aspect of geotechnical earthquake engineering practice since the Niigata earthquake in 1964. Based on liquefaction occurrences and field test data, a simplified procedure to analyze the potential for liquefaction was proposed by Seed and Idriss in [3]. This method became a standard analysis and widely used in practice. It has been continuously improved based on liquefaction histories from around the world [4]. Based on this procedure, Shibata and Teparaksa developed a method for evaluating liquefaction potential using the Cone Penetration Test [5]. Based on this method, liquefaction susceptibility analyses were conducted at several locations in the city of Padang after the 2009 earthquake, achieving good results [6]. Although these penetration-based methods (SPT and CPT) and the cyclic stress ratio are well developed, their use still requires advanced knowledge in choosing the parameters. Guidance for using penetration-based methods is discussed in [7].

In addition to the stress ratio in the soil mass, records of past liquefactions have shown that loose granular soils in saturated condition with poor drainage are more susceptible to liquefaction. Based on the results of past studies, several factors have been identified that effect soil liquefaction susceptibility [8], i.e. relative density (Dr); initial stress of the soil (s_i); mean grain size of the soil (D50); applied peak stress (s_d or t_{max}); duration of the motion (t); over-consolidation ratio (OCR); and initial pore pressure (u_i). In this paper, the results of liquefaction experiments in the laboratory related to the mean grain size and relative density of soil are presented.

Even though historically, sands were considered to be the only type of soil susceptible to liquefaction, liquefaction has also been observed in gravels and silts. Fine-grained soils that have strain-softening behavior may have a tendency to liquefy under a vibration load. Fine-grained soils are susceptible to this type of behavior if they satisfy the Chinese criteria [9], i.e. fraction finer than 0.005 mm < 15%; liquid limit (LL) < 35%; natural water content > 0.9 LL and liquidity index < 0.75.

Based on grain size analysis tests taken at several locations after the Kocaeli earthquake in Turkey in 1999 [10], grain distributions of liquefied soils are shown in Figure 1. The limit curves of soil compositions with liquefaction potential are also shown in this figure. The results of a sieve analysis of liquefied soil samples after the Padang earthquake in 2009 have been reported, as shown in Figure 2 [10]. The liquefied soil gradation boundary of Padang (shadowed) is in the middle area of the liquefaction chart limit of Aydan. From the Padang test results it can be seen that the distribution of liquefied soil particles is generally composed of fine sand by more than 60%. The fine content of soils that passes through sieve no. 200 was less than 20%. The mean grain sizes D50 of the soils were in the range of 0.15 mm to 0.35 mm.

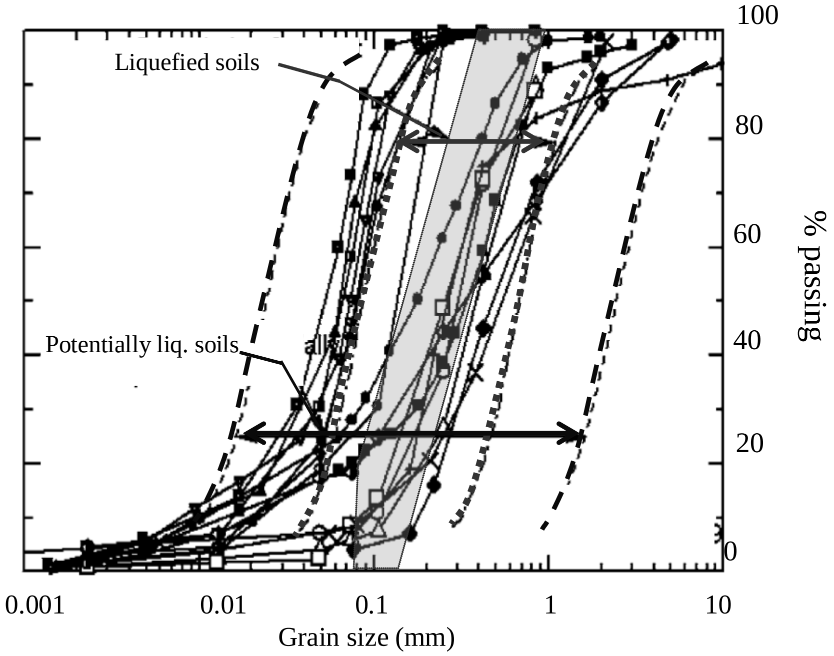

Figure 1 Grain size distribution limit for liquefaction [10].

A liquefaction potential assessment using the simplified method of Seed and Idriss was carried out at the coast of Padang and the grain distributions of soil samples are presented in [11]. The result of the assessment is shown in Figure 3, while the soil grain sizes are shown in Figure 2. This study obtained that the soil layers at depths of 4 m, 8 m, 10 m and 12 m were susceptible to liquefaction. Remarkably, the grain size distributions of these soil layers also matched the limit chart of liquefied soil. It is concluded that soil grain size distribution has a strong contribution in determining soil liquefaction potential.

Both relative density Dr and grain size D50 have been known to affect liquefaction potential. In this work, the grain size and relative density as well as the acceleration of the shaking were used as variables in laboratory tests to find the relationship between these parameters. Since this work was done in the laboratory, the parameters could be controlled. The soil samples were taken from the Padang city area and sieved to have different grain sizes.

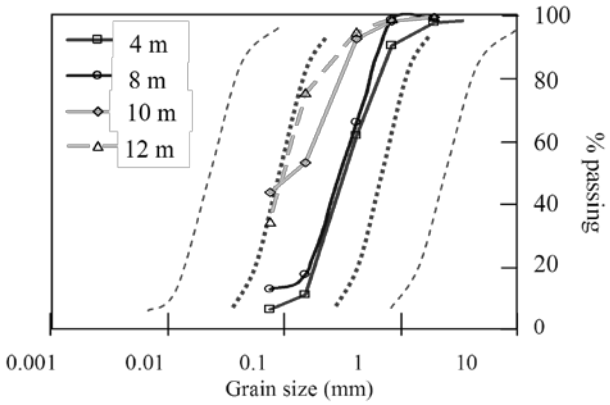

Figure 2 Soil grain distribution of Padang soil [11].

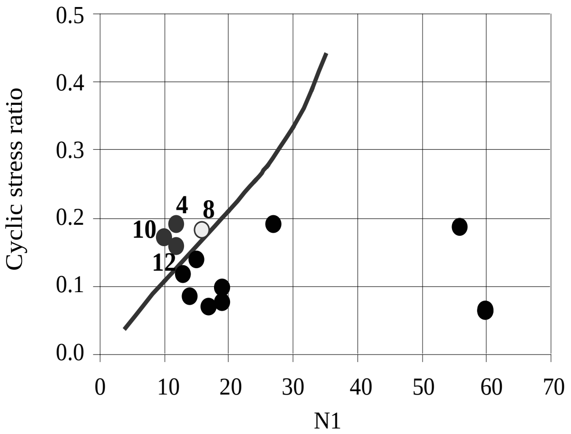

Figure 3 Liquefaction of Padang soil using the simplified method [11].

2 Effects of D50 and Dr on Liquefaction

Field case histories of liquefaction potential evaluation based on 50-year records from around the world were presented in [12]. Liquefaction occurrences in many places between 1944 and 1995 were reported, including soil investigation results. Based on this information, the mean grain sizes of soil D50 of liquefied soils can be summarized as shown in Table 1. It shows that from the 155 occurrences of liquefaction, as many as 78% of liquefaction cases occurred in soil with an average mean grain size between 0.1125 and 0.3375. The liquefaction histories proved that soil liquefaction is associated with the mean grain size of soil D50.

Table 1 Mean Grain Size Of Liquefied Soils*.

D_{50} (mm)	$D_{50.ave.}$ (mm)	Total Occur.	%	
0.03 – 0.075	0.035	4	3	11
	0.0575	13	8	
0.075 – 0.45	0.1125	52	34	78
	0.2	36	23	
	0.3375	33	21	
0.5 – 1.6	0.65	13	8	11
	1.425	3	2	
	1.6	1	1	
	Total:	**155**	**100 %**	

* Analyzed from [12].

Based on the same data as used in Table 1, a graph was made of the percentage of liquefaction occurrences with respect to average mean grain size, as shown in Figure 4. It can be seen that more than 80% of the liquefaction cases occurred in soils with mean grain sizes within the boundaries proposed by Aydan *et al.* (2008). This indicates that the mean grain size of the soil within a certain range has a significant effect on liquefaction potential.

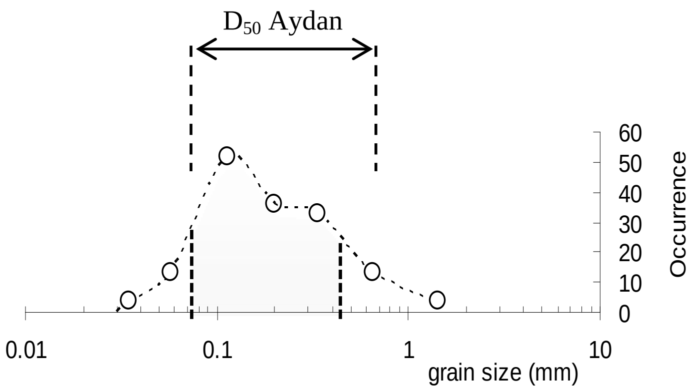

Figure 4 Liquefaction occurrence with mean grain size of soils.

The relationship between relative density and the cyclic stress ratio and number of cycles to liquefaction is presented in [13]. The relationship was obtained from the results of a number of liquefaction tests in the laboratory using triaxial equipment taken from a number of references from 1984 to 2006, as shown in Figure 5. For the same number of cycles, a soil with greater relative density has a greater cyclic stress ratio, which indicates the liquefaction resistance of the soil. It can be concluded that the relative density of soils is correlated to the liquefaction resistance.

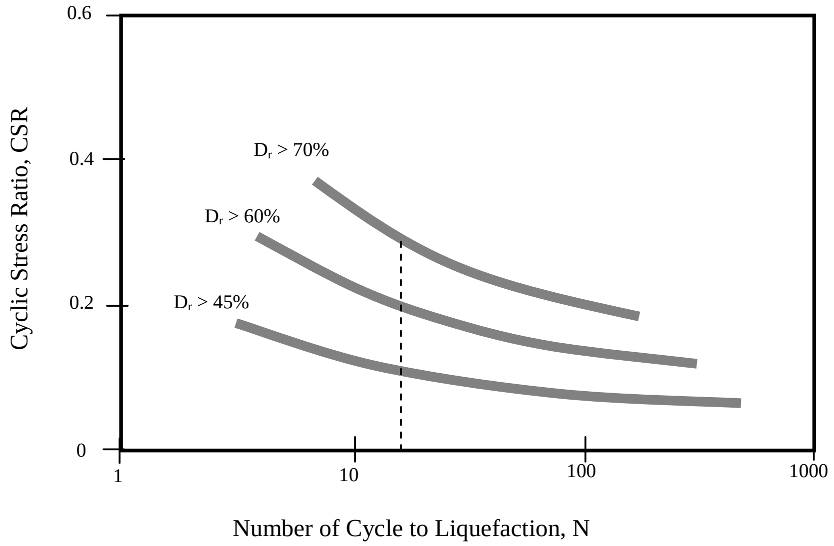

Figure 5 The effect of relative density on the relationship between cyclic stress ration and number of cycles (redrawn from [13]).

3 Laboratory Experiment

Past liquefaction experience associated with physical parameters inspired the present liquefaction study based on a series of tests in the laboratory. The two variations of soil parameters used in these tests were mean particle size and relative density of the soil. The soil samples were sands, prepared in uniformly graded ranges using standard sieves. Uniform samples were necessary to describe the relationship between mean grain size and liquefaction potential. Another variable of the samples in this experiment was the relative density (Dr) of the soil, which defines the ratio of soil densities in dry condition. Variation in relative density is proposed to describe the relationship between relative density and liquefaction potential.

Every laboratory test was done by placing a soil sample into a round container on a shaking table (Figure 6). The container was about 7 cm in diameter and 25 cm high. On top of the sample a steel indicator bar was placed, which allowed to settle down during shaking. The steel bar had a weight of 1.2 x 10^{-3} kN with a base cross section area of 1.68 cm^2. The soil sample was saturated prior to being placed in the container. The water table in the sample was adjusted to just above the surface of the sample to keep the soil in saturated condition. The test specimen was then vibrated at a certain acceleration. The vibration was sinusoidal for 25 seconds at a frequency of 13 Hz.

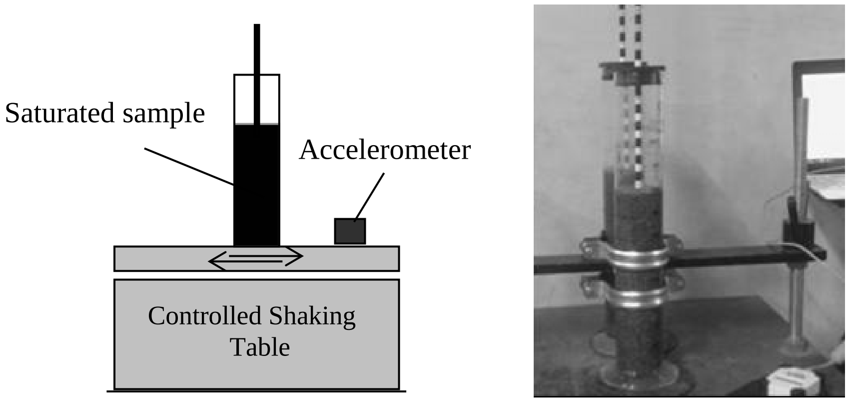

Figure 6 Laboratory test sketch and photograph.

As in field liquefaction, the propagation of shear waves causes the sand mass to loose contact and increases the pore water pressure. Since the seismic shaking occurs over a short time period, the soil performs as an undrained material. In liquefied condition, the effective stress in the soil body is decreased and thus the shear strength of the soil can essentially drop off to zero. In this condition, every individual soil particle is released from any confinement [14]. The liquefied soil mass then will fail to support a building's foundation, which results in excessive settlement of the building that sits on it. The same phenomenon could be observed when liquefaction occurred in the test samples: the shear strength of the soil dropped, so the indicator bar settled down. In this study, the acceleration and settlement of the indicator bar were recorded during shaking.

4 Experiment Results

In order to investigate the effects of relative density on shaking resistance, the results of the vibration experiments conducted on the samples of soil between sieve no. 100 and 200 are shown in Figure 7. It can be seen that for the same acceleration and time, a smaller relative density of the soil samples had greater settlement. The same results plotted on a logarithmic scale are shown in Figure 8. There is a remarkably similar pattern in the form of settlement for each relative density. The time to start the initial settlement tends to increase with the increase of relative density, i.e. denser soils need a longer time to start initial settlement. These results are similar to those presented in [13], where a higher relative density had a greater liquefaction resistance.

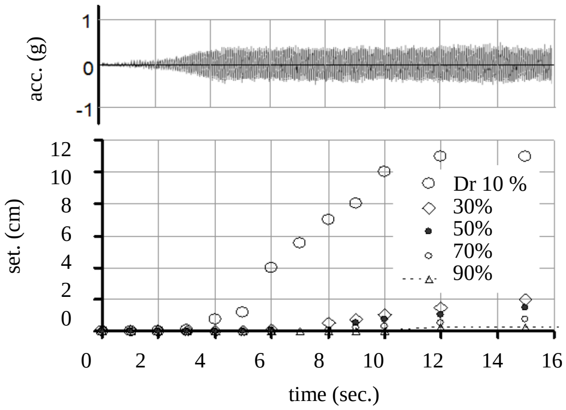

Figure 7 Settlement versus shaking time.

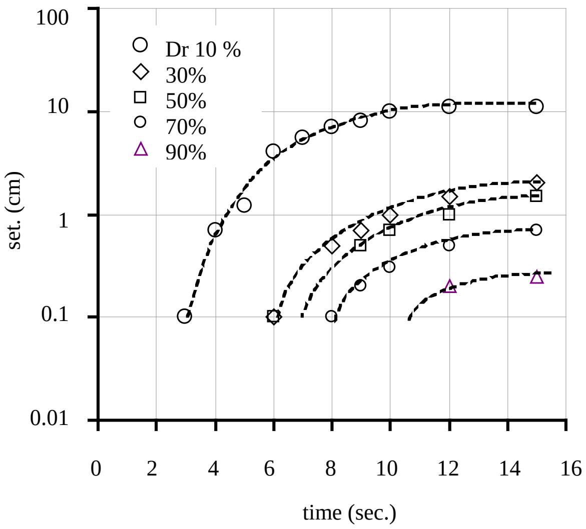

Figure 8 Time versus settlement plotted in a logarithmic scale.

In this experiment, apart from the variations of mean grain size and relative density of the soil samples, also different maximum accelerations of 0.3 g and 0.6 g were applied. These acceleration values were based on the Padang earthquake in 2009 (0.3 g acceleration) and the Indonesian seismic regulations for the Padang region (0.6 g acceleration). Table 2 shows the test results for shaking at an acceleration of 0.3 g. These results are plotted in Figure 9, together with the result of the shaking test for 0.6 g acceleration.

Table 2 Settlement rate from shaking test results.

	Sieve no:	200-100	100-80	80-60	60-40	40-20	20-10	10-4	
	ave.size (mm)	**0,113**	**0,165**	**0,215**	**0,338**	**0,638**	**1,425**	**3,375**	
Dr (%)	10	1,43	0,13	0,10	0,08	0,05			settlement rate (cm/sec.)
	30	0,25	0,14	0,09	0,07	0,05			
	50	0,20	0,10	0,05	0,04				
	70	0,09	0,07	0,03					
	90	0,03	0,07	0,02					

In order to separate the test results with the two different criteria, the settlement rate value was calculated. First, a settlement limit of 2.54 cm (1 inch) for general foundation stability was adopted. Second, the shaking duration of big earthquakes – usually about 25 seconds (or longer) – was taken. Comparison of these values then produced the rate of settlement during shaking, which was about 0.1 cm/sec. Taking this limit as the separation criterion for the settlement rate value, the linear boundary line for each acceleration (0.3 g and 0.6 g) could be plotted as shown in Figure 9.

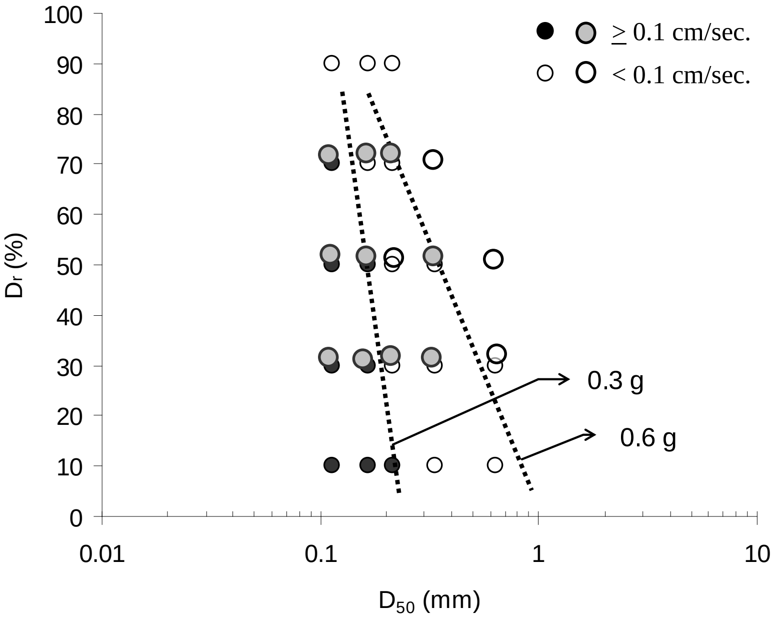

Figure 9 Relative density versus grain size relationship for accelerations of 0.3 g and 0.6 g.

These results provide a unique relationship between mean grain size and relative density related to the settlement rate value. The settlement rate value can be taken to interpret the liquefaction potential. Particles with the same mean grain size and a different relative density also have a different liquefaction potential. A soil with larger mean grain size and larger soil density may have greater liquefaction resistance. For example, with a shaking acceleration of 0.3 g, the soil with 0.25 mm mean grain size will easily liquefy with its relative density equal to 10%. However, the same soil will have increased liquefaction resistance when the relative density is increased by 30%. For 0.6 g acceleration, the same soil with a mean grain size of 0.25 mm will liquefy when the relative density is less than 70%.

5 Conclusions

Liquefaction histories from the past show that there are many factors that can be associated with the liquefaction susceptibility of soil deposits. These factors can be in the form of the mechanical and the physical properties of the soil as well as the characteristics of the earthquake. Liquefaction resistance of sands increases with relative density. In terms of the mean particle size of sands, there is a certain boundary where uniform sand particles become susceptible to liquefaction.

The shaking test results of sand samples presented in this paper show that both relative density and mean particle size have a unique relationship with respect to the resistance of sand soil against shaking. Apart from the stress in the soil mass, these factors may need to be considered in liquefaction potential assessment. There is a limit value of the relative density of the soil with respect to its mean grain size associated with liquefaction resistance.

Acknowledgments

I would like to thank my students Yorizal Putra and Saut Pantas Siahaan for assisting in the laboratory experiments. I would also like to thank the Engineering Faculty of Andalas University for providing the financial means.

References

[1] Day, R.W., *Geotechnical Earthquake Engineering Handbook*, The McGraw-Hill Comp., New York., USA, 2002.
[2] Kramer, S.L., *Geotechnical Earthquake Engineering*, Prentice Hall, Englewood Cliffs, New Jersey, USA, 1996.
[3] Seed, H.B., & Idriss, I. M., *Simplified Procedure for Evaluating Soil Liquefaction Potential*, J. Geotech. Engg. Div., ASCE, **97**(9), pp. 1249-1273, 1971.

[4] Seed, H.B. & Idriss, I.M., *Ground Motion and Soil Liquefaction during Earthquake*, Earthquake Engineering Research Institute, Berkeley, 1982.

[5] Shibata, T. & Teparaksa, W., Evaluation of Liquefaction Potential of Soils Using Cone Penetration Tests, J. Soils and Foundations, **28**(2), pp. 49-60, 1998.

[6] Hakam, A., *Soil Liquefaction of Padang due to Padang Earthquake 30s'09*, The Journal of Civil Engineering Dimension, **14**(2), pp. 64-68, 2012.

[7] Youd, T.L. & Idriss, I.M., *Liquefaction Resistance of Soils: Summary Report from The 1996 NCEER and 1998 NCEER/NSF Workshop on Evaluation of Liquefaction Resistance of Soils*, J. Geotechnical and Geoenviron. Eng., ASCE, **127**(10), pp. 817-833, 2001.

[8] Das, B.M., *Fundamental of Soil Dynamics*, Elsevier Pub., New York, 1989.

[9] Wang, W.S., *Some Findings in Soil Liquefaction*, Report Water Conservancy and Hydroelectric Power Scientific Research Institute, Beijing, China, pp. 1-17, August 1979.

[10] Aydan, O., Ulusay, R. & Atak, V.O., *Evaluation of Ground Deformations Induced by the 1999 Kocaeli Earthquake (Turkey) at Selected Sites on Shorelines*, Environ. Geol., **54**(1). pp. 165-182, 2008

[11] Hakam, A. & Darjanto, *Liquefaction Potential Assessment of Padang Beach Based on Grain Size and Standard Penetration Resistance*, Jurnal Teknik Sipil – ITB, **20**(1), pp. 33-38, 2013. (Text in Indonesian).

[12] Cetin, K.O., Seed, R.B., Moss, R.E.S., Der Kiureghian, A., Tokimatsu, K., Harder, Jr., L. F., & Kayen, R.E., *Field Case Histories for SPT-Based In Situ Liquefaction Potential Evaluation*, Geotechnical Engineering Research Report No. UCB/GT-2000109, Department of Civil and Environmental Engineering, California University, Berkeley, 2000

[13] Zhou, Y. & Chen, Y., *Laboratory Investigation on Assessing Liquefaction Resistance of Sandy Soils by Shear Wave Velocity*, J. Geotechnical and Geoenviron. Eng., ASCE, **133**(8), pp. 959-972, 2007.

[14] Ishihara. K., *Stability of Natural Deposits during Earthquakes, Proc. The 11th International Conf. on Soil Mechanics and Foundation Engineering*, San Francisco, **1**, pp. 321-376, 1985.