An Experimental Study on the Liquefaction of Saturated Soil, Using Shaking Table

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Abstract

Following the previously reported experiments[1], an experimental study on the liquefaction of saturated Shirasu using shaking sand box was carried out. It was concluded from these experiments that the stress condition in which saturated Shirasu liquefied was almost the same as in the case of Toyoura sand.

Besides, taking advantage of the fact that, at this shaking table, the frequency of the vibration could be changed automatically and periodically within the range of the frequency previously set up, experiments under variable acceleration was carried out and its effect on the liquefaction of soil was inquired.

It was clarified as a result that the average equivalent acceleration α_{av} could be calculated from the formula (3).

Introduction

One of the experimental methods to realize the phenomenon of the liquefaction of saturated soil is the method using the shaking sand box. In this method, a sand box is placed on the shaking table and vibrated, and the phenomenon of the liquefaction of saturated soil in that box is persuaed.

Through this method, we have already carried out the experiment on two kinds of sand and have acquired some knowledges on the relations amonge various factors having influences on the soil liquefaction. This time, we have carried out similar experiments on the saturated Shirasu.

Moreover, in contrast to the experiments of saturated sand carried out so far under constant acceleration, experiments under variable acceleration was carried out and the differences in the occurrence of the soil liquefaction was compared.

The results of these experiments will be mentioned hereafter.

Experimental method and soil

The method of experiment using shaking sand box is stated in detail in the previous paper. This time, however, the structure of the sand box is modified a little, because the Shirasu of less permeability was chosen as soil.

Namely, in order to dissipate the pore water pressure set up when the air pressure is applied on the surface of Shirasu layer as fast as possible, a vinyl

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chloride plate in which a porous stone is embedded is placed at the bottom of the shaking sand box. Owing to that, the pore water in the saturated soil in the shaking sand box can be drained out quickly. The sketch of the structure is shown in Fig. 1.

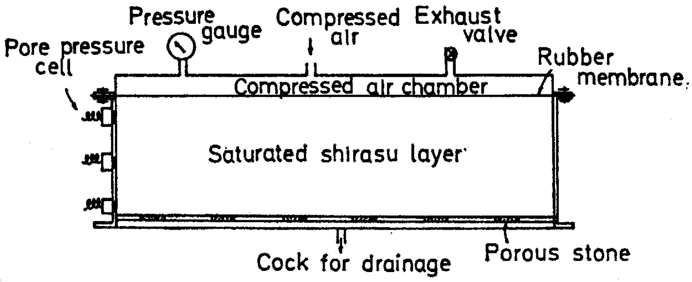

Fig. 1 Shaking sand box.

The soils used in the experiments were Shirasu obtained in Miyazaki prefecture and Shingu coarse sand used in the previous experiments. Concerning Shirasu the materials which passed the 5 mm sieve were used.

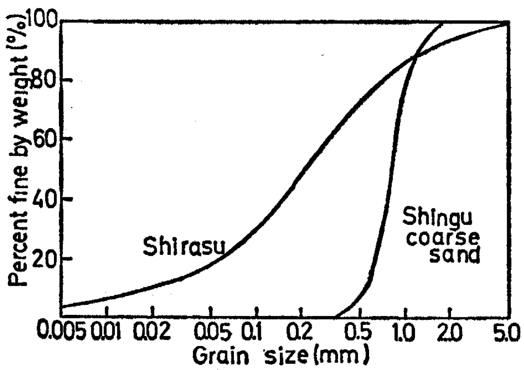

Fig. 2 Grain size distribution curves.

Table 1. Properties of soil used in this test.

	Shingu sand	Shirasu
Specific gravity. Gs	2.64	2.34
50% Grain size. D_{50}	0.82 mm	0.21 mm
Uniformity coefficient. Cu	1.35	12.61
Maximum void ratio. e_{max}	0.89	1.609
Mimimum void ratio. e_{min}	0.56	0.79
Angle of inter friction. ϕ	36°	30°
Dynamic angle of inter friction. ϕ_d	26°	28.5°

It must be noted that the experiments on Shirasu were carried out under constant acceleration and the experiments under variable acceleration were carried out on Shingu coarse sand.

Experimental results and the discussions

Experiments under constant acceleration The following are known from the results of previous experiments:

On the liquefaction of sand layer, the smaller the initial effective pressure, the smaller the acceleration which cause the liquefaction of that layer. The latter is approximately proportional to the former. Under the same initial effective pressure, smaller the acceleration, the longer the shaking duration to cause liquefaction.

It was inquired if the same results were obtained on Shirasu. Fig. 3 shows an example of experimental results on Shirasu. As shown in it, as the vibration of the shaking table goes on under the constant acceleration, the pore water pressure in Shirasu continues to increase at an approximately constant rate. But at a certain time, suddenly increase the pore water pressure and its amplitude and then the occurrence of the soil liquefaction is recognized. But the increase is not so clear as in the case of sand layer.

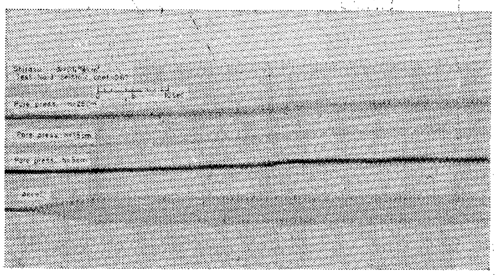

Fig. 3 Record of shaking table test.
(Constant acceleration test)

Through analysing these data, the relations among the seismic coefficient k, the pore water pressure immediately before the liquefaction u_f, the acceleration at which the soil liquefaction took place and the shaking duration to cause liquefaction t_L, were clarified. It must be noted that the experiments were carried out under the initial effective pressure $\sigma'_v=0.1$, 0.2 and 0.3 kg/cm^2.

Fig. 4 and Fig. 5 show the results of these analyses.

From the restriction of the vibrating force of the shaking table, the experiments were carried out at the vibration frequency of 10 c/s under the initial effective pressure $\sigma'_v=0.3$ kg/cm^2, at 5 c/s under $\sigma'_v=0.2$ kg/cm^2 and at 4 c/s under $\sigma'_v=0.1$ kg/cm^2.

These differences in the frequency are supposed to have some influences on the results of the experiments, but these were neglected in analysing the experiment data.

Fig. 4 shows the relation between the seismic coefficient and the shaking duration to cause liquefaction.

In this figure, the experimental curve obtained in case of $\sigma'_v=0.3$ kg/cm^2 is found to have a different gradient from those of other curves.

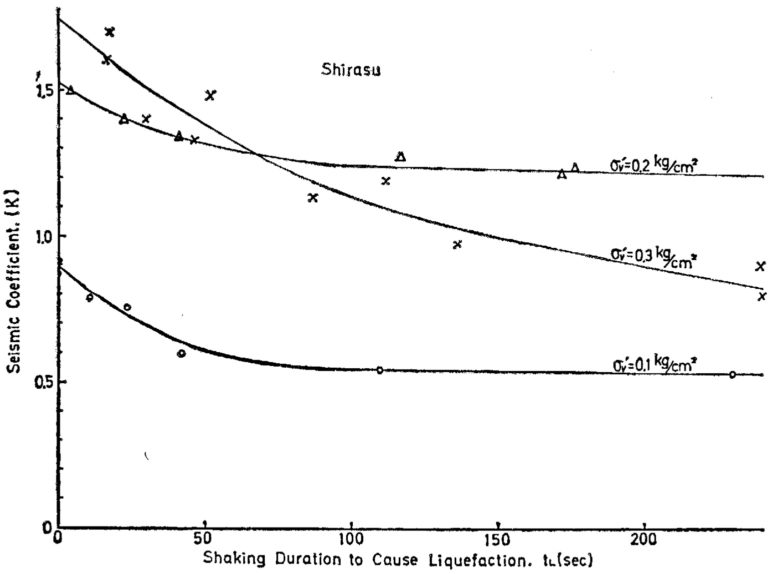

Fig. 4 Relationship between seismic coefficient and shaking duration to cause liquefaction.

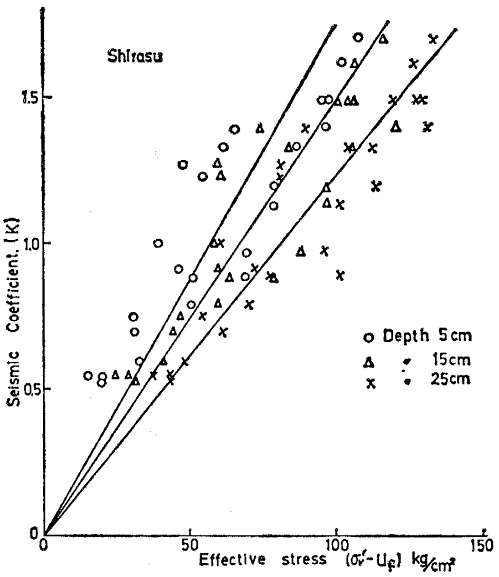

Fig. 5 Relationship between effective stress and seismic coefficient.

This is because the frequency in the case of the experiment under $\sigma_v'=$ 0.3 kg/cm^2 was substantially different from those of other cases.

Now, considering that the formula which shows the condition of the liquefaction of saturated soil is

$$\tau_d=(\sigma_v'-u_f)\tan\phi \qquad \cdots\cdots\cdots(1)$$

in which

τ_d: shearing stress induced by the vibration
σ_v': initial effective pressure applied to the saturated soil layer
u_f: pore water pressure immediately before the liquefaction

ϕ: angle of internal friction of the saturated soil

the relation between $(\sigma'_v - u_f)$ and seismic coefficient k, which is shown in Fig. 5, is obtained to confirm the above formula. The relations between $(\sigma'_v - u_f)$ and k are indicated in three different straight lines according to the records of the depth 5, 15 and 25 cm respectively. In our judgement, these differences are due to the differences in the density of the Shirasu layers. The apparent densities actually measured on the upper, middle and lower layer of Shirasu in the sand box were $\gamma_d = 1.12$, 1.18 and 1.32 g/cm^3 respectively.

The relation

$$k \propto (\sigma'_v - u_f) \qquad \cdots\cdots\cdots(2)$$

is confirmed from Fig. 5 and the proportional coefficients can be obtained from their gradients.

Since the relation between τ_d and k can be obtained from the formulae (1) and (2), k can be substituted for τ_d.

Then, obtaining the stress ratio (τ_d/σ'_v), the relation between this and the shaking duration is shown in Fig. 6.

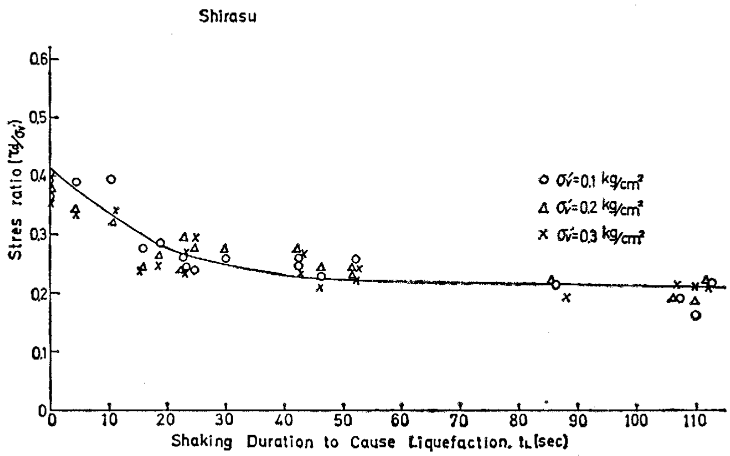

Fig. 6 Stress ratio τ_d/σ'_v required to cause liquefaction.

Experimental values under various σ'_v are concentrated around a straight line though there are some scattering, therefore, as in the case of sand layer, (τ_d/σ'_v) is understood to be an important index concerning the occurrence of the liquefaction in Shirasu layer.

The likeliness of the liquefaction of Shirasu layer is shown in Fig. 7, together with the results of previous experiments on Shingu coarse sand and Toyoura sand. These results of analyses disclose that the critical value of (τ_d/σ'_v) necessitated for the liquefaction is the value of (τ_d/σ'_v) when the shaking duration to cause liquefaction is infinite.

These critical values are 0.175 in Shingu coarse sand, 0.220 in Toyoura fine sand and 0.210 in Shirasu. The larger this critical value, the larger the shearing force necessitated to cause liquefaction. Therefore, compared with saturated sand, saturated Shirasu has the same degree of dangerousness as fine sand, as far as the liquefaction due to vibration is concerned.

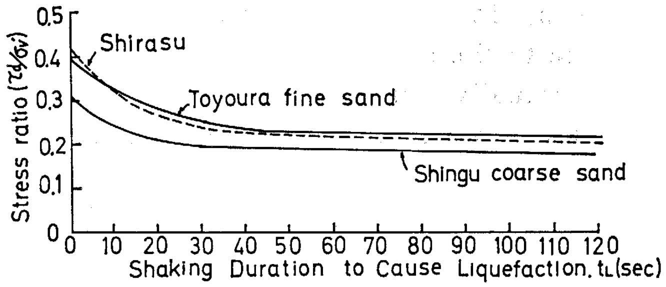

Fig. 7 Comparison of stress ratio τ_a/σ_v' required to cause liquefaction of three kind's of soil.

Experiments under variable acceleration Fig. 8 is an example in the case of Shingu coarse sand. Two methods are considered in applying variable acceleration. The one is to change the amplitude under constant frequency and the other is to change the frequency under constant amplitude. The latter was chosen in our experiments. The following two kinds of the range of variable frequency were chosen: (1) 120～280 cpm, (2) 200～280 cpm. But as shown in Fig. 8 the frequency was changed at constant period.

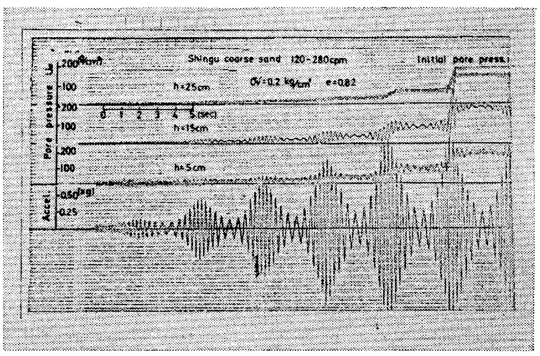

Fig. 8 Record of shaking table test. (Variable acceleration test)

The relation between k (maximum value) and t_L as well as the relation between k (maximum value) and the effective pressure at the begining of the liquefaction $(\sigma_v'-u_f)$, which were obtained through analysing each experimental dat, are shown in Fig. 9 and Fig. 10.

Now, in the case of variable acceleration, we thought out the idea of average equivalent acceleration α_{av}, in order to clarify the evaluation of the magnitude of variable acceleration in comparison with constant acceleration.

$$\alpha_{av}=\frac{\Sigma\alpha_i n_i}{\Sigma n_i} \qquad \cdots\cdots\cdots(3)$$

in which

α_i: acceleration of each wave

n_i: number of waves with acceleration α_i

The value α_{av} of shingu coarse sand calculated using the formula (3) in the cases of frequency range 120~280 cpm and 200~280 cpm is 57% and 74% of maximum acceleration respectively. And the equivalent frequency which is defined as the number of vibrations per minute is 190 cpm and 250 cpm respectively. Therefore, in order to compare with the experiment results under constant acceleration, the shaking durations to cause liquefaction obtained in these experiments were corrected through being multiplied by (190/240) and (250/240) respectively. These results are shown in Fig. 11. And Fig. 11 shows that these are in good accordance with the results of experiments under

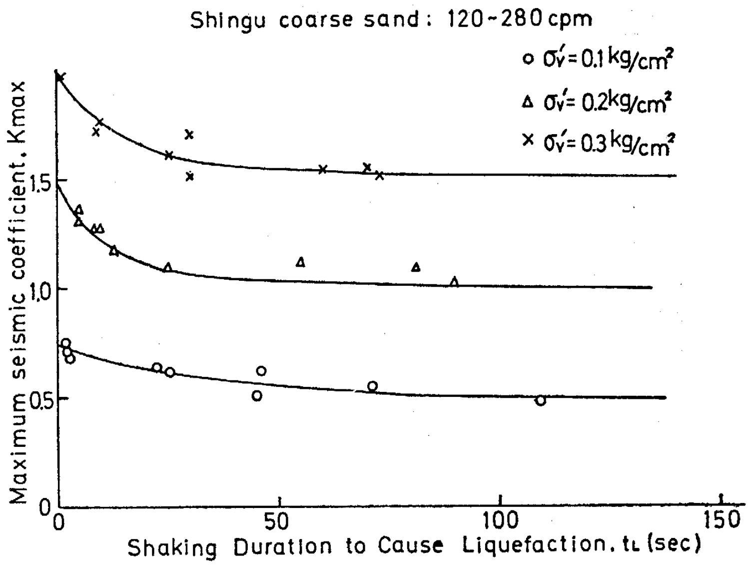

Fig. 9(a) Relationship between seismic coefficient and shaking duration to cause liquefaction.

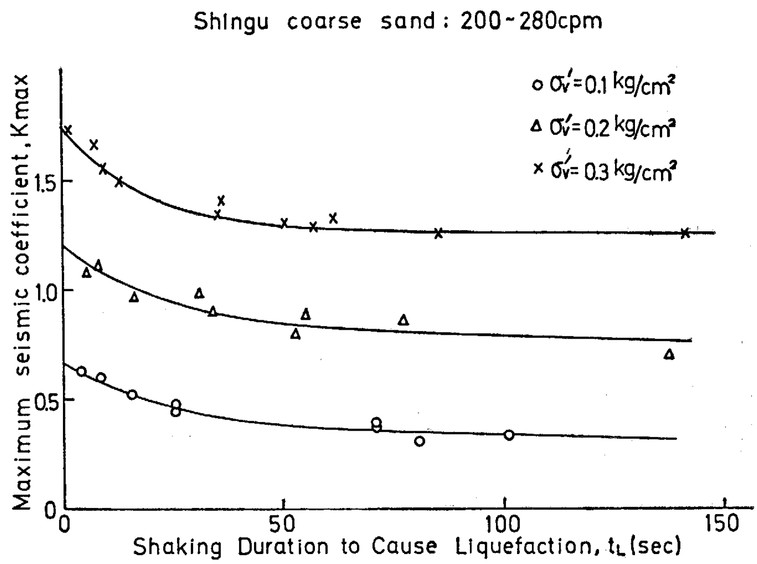

Fig. 9(b) Relationship between seismic coefficient and shaking duration to cause liquejaction.

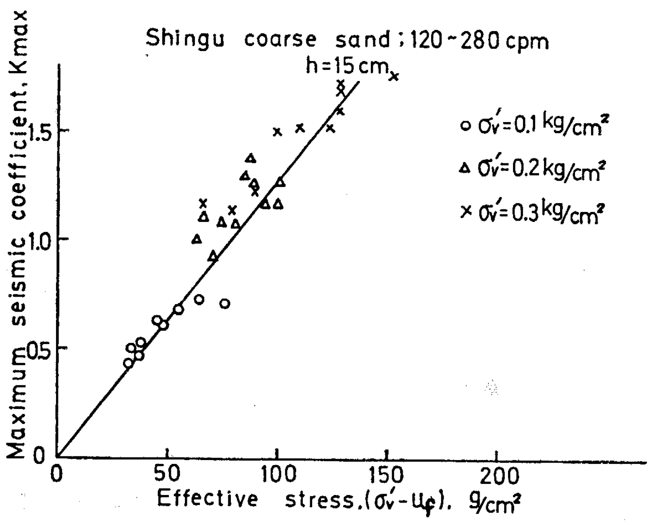

Fig. 10(a) Relationship between effective stress and seismic coefficient.

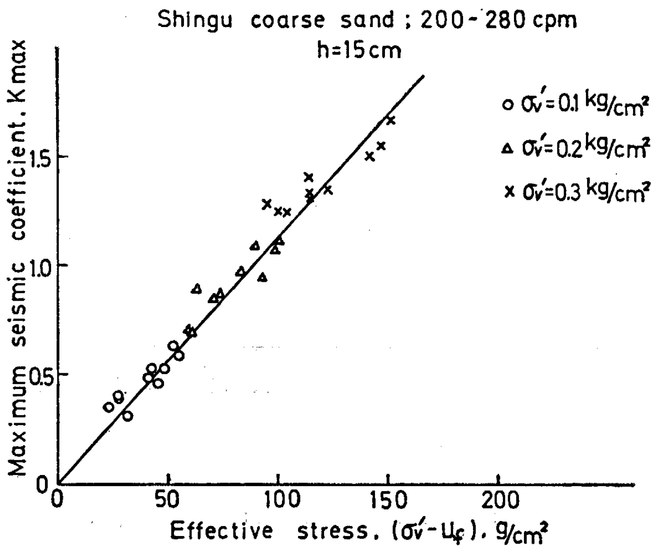

Fig. 10(b) Relatioship between effective stress and seismic coefficient.

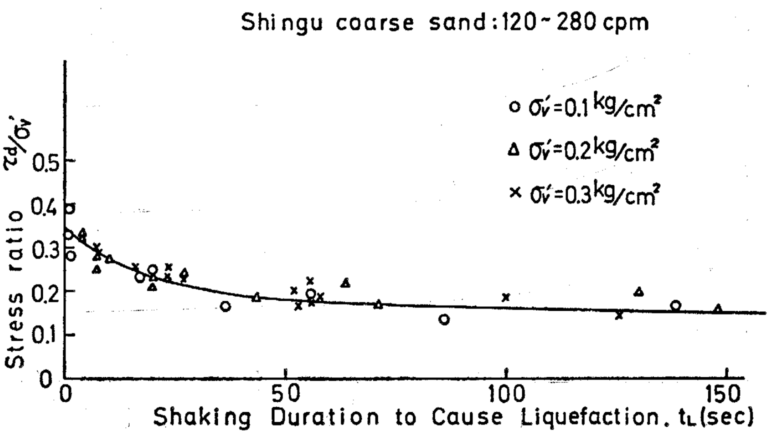

Fig. 11(a) Stress ratio τ_d/σ_v' required to cause liqueaction.

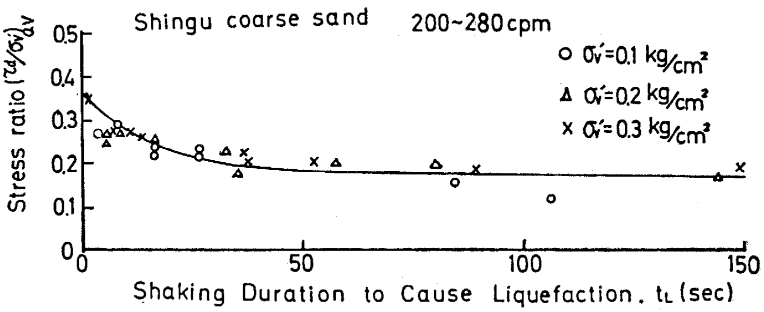

Fig. 11(b) Stress ratio τ_d/σ'_v required to cause liquefaction.

constant acceleration. It can be pointed out that these values of α_{av} are very close to Seed[2)] and other's average equivalent shearing force which is 65% of maximum shearing force.

Conclusion

(1) The critical stress ratio $(\tau_d/\sigma'_v)_{cr}$ in which the liquefaction of saturated Shirasu occures was clarified to be approximately 0.210 through the experiments under constant acceleration, although it can not be directly compared with the experiment results of sand because the Shirasu used in these experiments had different grain size distribution from that of sand. Since the critical stress ratio of Shingu sand and Toyoura sand is approsimately 0.175 and 0.220 respectively, there is a possibility of liquefaction in saturated Shirasu.

(2) When the variable acceleration is applied to the saturated soil layer, to evaluate the magnitude of acceleration of vibration, it is recommended to use the following average equivalent acceleration,

$$\alpha_{av}=\frac{\Sigma\alpha_i n_i}{\Sigma n_i}$$

(3) The shaking duration to cause liquefaction t_L is closely related to the stress ratio of cyclic shearing stress to the confining pressure (τ_d/σ'_v), independent of the wave form of acceleration of the vibration.

Acknowledgement

The author is deeply indebted to Mr. Akira Miyauchi, exresearch assistant and Mr. Nobuo Fujii, a reseach assistant in the author's university, for his aid in the present experiments and his helpful discussion.

Symbols used in the paper

e: Void ratio

t_L: Shaking duration to cause liquefaction

u_f: Pore pressure in initial liquefaction

ϕ: The angle of internal friction
σ_v': Initial effective normal pressure

References

1) O-hara Sukeo: "The results of Experiment on the Liquefaction of Saturated Sand with a Shaking Box: Comparison with Other Methods" Technology Reports of the Yamaguchi university, **1,** 121–139 (1972).
2) Seed, H. B. and Idriss, I. M.: "Simplified Procedure for Evaluating Soil Liquefaction Potential" Proc. ASCE, **97,** SM 9, 1249–1273 (1971).