2003 Pacific Conference on Earthquake Engineering

Desaturating sand deposit by air injection for reducing liquefaction potential

M. Ishihara, M. Okamura & T. Oshita

Public Works Research Institute, Tsukuba City, Japan.

ABSTRACT: It has been known that unsaturated sands have a significantly higher resistance to liquefaction than saturated sands. Liquefaction potential of saturated sand can be reduced if the degree of saturation of the sand is effectively lowered. A centrifuge model test was performed, in which air was injected into a saturated ground model through a vertically penetrated pile, to see how wide the air injected from the tip of the pipe spread in the originally saturated ground.

Undisturbed high-quality samples were taken by the ground freezing method from grounds improved with the sand compaction pile. The degree of saturation of the ground was found to be unusually low due to a large amount of air exhausted in the ground during sand pile construction. Results of hollow cylindrical undrained cyclic shear tests on the samples indicted that the resistance to liquefaction of the ground was significantly enhanced by the de-saturation during SCP construction. The liquefaction resistances of the improved sand are considered to be higher than those obtained from the *N*-value based conventional method which is only available for fully saturated soils.

1 INTRODUCTION

Sand compaction pile (SCP) techniques have extensively been used as a recent way to ameliorate liquefaction resistance of loose sand deposits. The principal of this ground improvement technique is the densification of foundation soils by installation of sand piles in the ground. Increases in soil density as well as lateral effective stresses are considered to enhance liquefaction resistances of foundation soils.

In this ground improvement technique sand piles are built in the ground in by penetrating a casing pipe into the ground to a specified depth. The casing is then withdrawn, and the sand is discharged into the bored hole with aid of pressurized air of the order of 500 kN/m^2, supplied from the top of the casing. It may be expected, therefore, that the ground improved with SCP contain considerable amount of air. In fact, Tokimatsu et al. (1990) reported that primary wave velocities observed in a SCP improved ground were unusually low, indicating the soil was unsaturated.

Since the degree of saturation of soil, S_r, has a significant effect on the liquefaction resistance (Sherif et al., 1977; Martin, et al., 1978; Yoshimi et al., 1989), it is important to investigate degree of saturation of grounds improved with SCP. Cyclic shear tests conducted by Yoshimi et al. (1989) have indicated that a 10 % decrease in S_r doubled the liquefaction resistance of loose to medium dense sand. Not only the densification effect, but also the desaturation effect improves the liquefaction resistance of the ground through the SCP method. Conversely, only the densification effect is taken into account in current design practices.

In this study, a centrifuge test was conducted first to see how widely the air injected from the tip of casing pipe, spread in the originally saturated ground. Then, high quality undisturbed samples were obtained from three SCP improved sites by using the ground freezing method, aimed at investigating the distribution of saturation in the improved ground. The degree of saturation of the samples was measured and undrained cyclic shear tests on the samples were conducted to explore the liquefaction resistances of the sands.

2 CENTRIFUGE TEST

2.1 *Model preparation*

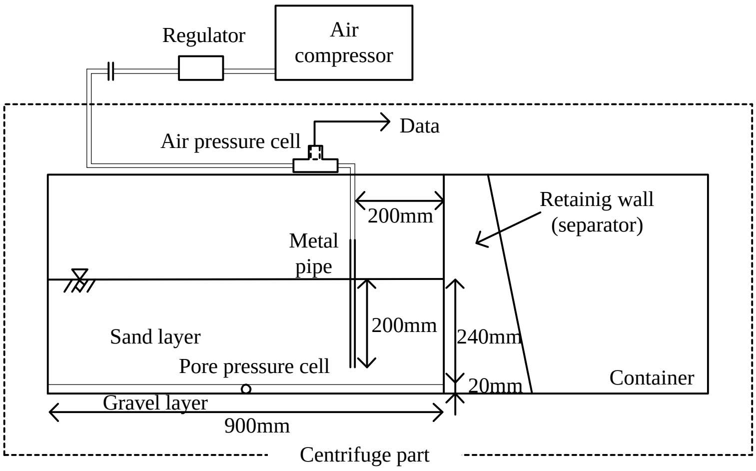

Fig.1 Cross section of centrifuge test model

A centrifuge test was conducted, where air was injected into saturated ground models through a vertically penetrated pile. A cross section of the model is illustrated in **Fig.1**, which was prepared in a rigid model container with internal dimensions of 500mm high, 1500mm wide and 300mm deep. The horizontal model ground consisted of a gravel layer underlying a sand layer. Considering the similitude of centrifuge modelling, the model ground was saturated with a viscous fluid with a viscosity of about 40 times the viscosity of water. The sand layer was prepared with Edosaki sand to be in a medium dense condition with a saturated density of 1.86g/cm^3. The water table level in the model approximately coincided with the ground surface. A pore pressure cell was set on the bottom of the container to monitor the change in the ground water table, as shown in **Fig.1**. A metal pile with an internal diameter of 5mm was penetrated into the model ground to the depth of 200mm from the ground surface. The top of the pipe was connected to a compressor with a flexible tube, via a pressure cell and a regulator so that air pressure can be controlled manually throughout the experiment. The bottom of the pipe was covered with a wire net to prevent the pipe from being choked up with the sand, and therefore air pressures at the pressure cell and at the tip of the pipe were assumed to be the same.

After the model was brought up to the 245 m/sec^2 (25g) centrifugal acceleration, air pressure was increased and decreased step by step as shown in **Fig.2(a)**. The pore pressure at the bottom and the air pressure were measured and a plan image of the model was captured with a video camera.

This model simulates a fully submerged 6m deep sand with a 125 mm diameter pipe installed to a depth of 5 m. In the following discussions all results and comparisons are presented in prototype units unless otherwise mentioned.

2.2 *Results and discussion*

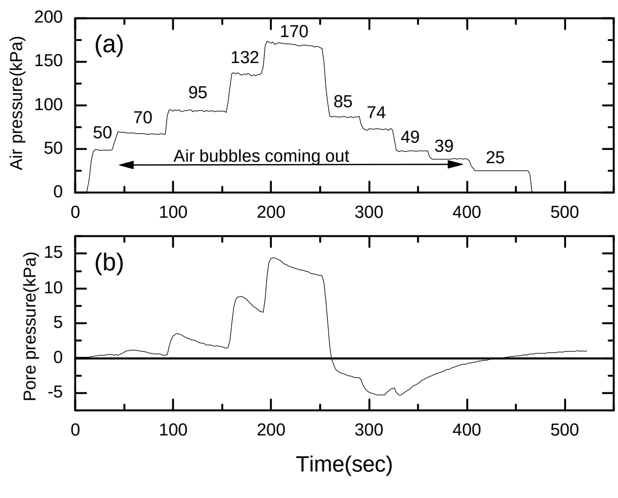

Fig.2 Time history of air pressure and excess pore pressure at the bottom of the sample ground model

Figure 3 shows a transition of regions in which air bubbles continuously spouted from the ground surface at steps of air pressures increases 50, 70, 95, 132 and 170kPa. It should be noted that the air bubbles spouted from everywhere of the ground surface within the region. This fact indicates that the soil below the region was uniformly desaturated during the test. The approximate diameter of the region was 5 m at the air pressure of 95 kPa. In practice, sand piles in SCP method are installed in a ground at an interval mostly less than 2.5 m, and air pressure in the casing is of the order of 500 kPa. An entire

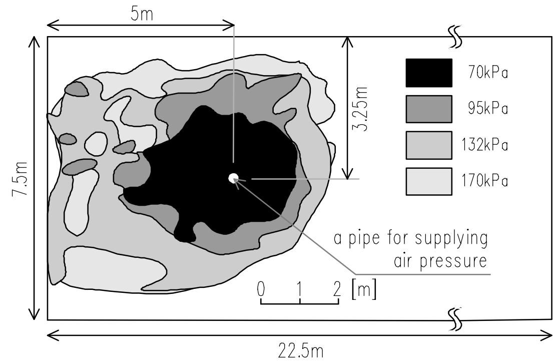

Fig.3 Transition of regions in which air bubbles came out, improved regions, in steps increasing air pressure

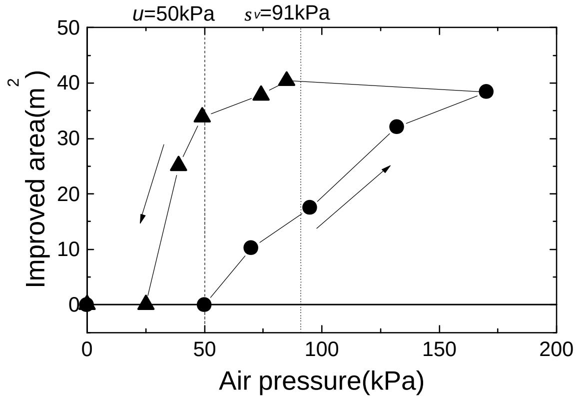

Fig.4 Relationship of supplied air pressure and improved area

area of SCP improved ground is considered to be covered with the desaturated soil.

Although some enclaves occurred, the regions appear as rough concentric circles, and grow gradually as the air pressure became larger.

Figure 4 plots area of the region in relation to the air pressures. Air bubbles first came into sight when the air pressure reached 70kPa and thereafter the area of the region increased almost linearly with pressure. The hydrostatic pressure, u, and the vertical total stress, s_v, at the depth of the pipe tip were about 50kPa and 91kPa, respectively. Air pressure higher than the hydrostatic pressure was needed to inject air into the ground.

Residual pore pressure at the end of the test was 1.03kPa as depicted in **Fig.2(b)**, indicating that the water level rose 0.1 m as compared with that at the beginning of the test. Volume of air entrapped in the ground can be then calculated by multiplying the area of the soil container by the change in the water table, that is 22.5 m * 7.5 m * 0.1 m = 16.9 m^3. Assuming that ground under the maximum area of the region (= $40m^2$) was desaturated uniformly, we have the degree of saturation of the soil in the region to be 85.8%. This estimation may provide an upper bound of the degree of saturation because the diameter of desaturated zone in the ground is presumed to decrease with depth.

3 DEGREE OF SATURATION AND LIQUEFACTION RESISTANCE OF SAND IMPROVED WITH SCP

In constructing sand compaction piles, it is common practice to use a casing pipe that is penetrated into the ground and sand is inserted into the casing from the top. Pressurized air of the order of 500 kN/m^2 is supplied from the top of the casing to aid pushing sand down the casing. Thus, large amount of air is injected into the ground with sand. In this study, high quality undisturbed samples were obtained at three sites, where foundation soils were improved with the SCP technique. Laboratory tests on these samples were conducted to investigate the distribution of degree of saturation and liquefaction resistances of the sands.

3.1 *Sampling of frozen sand and in-situ tests*

The sampling and in-situ tests were conducted at sites at Niigata, Izumo and Yasugi, as shown in **Fig.5**. High quality undisturbed samples were obtained by the in-situ freezing method using a single freezing pile (Yoshimi et

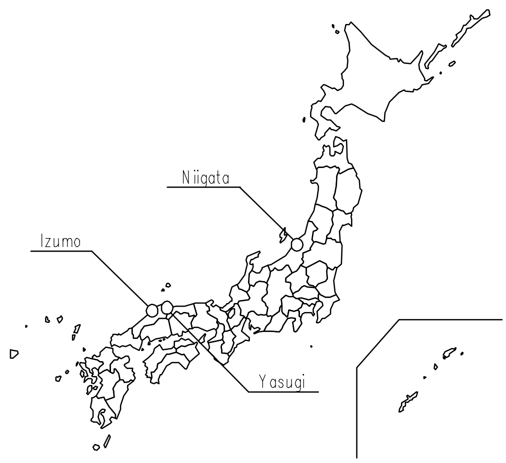

Fig.5 Locations of sites

al., 1978) immediately after construction of SCP. The procedure of the in-situ freezing and the sampling of frozen sands is schematically illustrated in **Fig.6**. The freezing process was performed very carefully, where temperatures in the ground were monitored by thermocouples to prevent disturbing the samples by expansive strains during freezing. For example, at the Niigata site, it took about 3 days for the samples to freeze, when the diameter of the frozen zone became 1200mm. The quality of the samples obtained at these sites was high and the state of air bubbles in the ground was also expected to be confined in ice in the same condition as that before freezing.

Frozen sand samples of 150mm in diameter were obtained by using a 150mm core barrel. The coring was done at several different locations in each site as indicated in **Fig.7**, avoiding the zone 70mm from the surface of the freezer pile, where the sands could be disturbed by a borehole excavation for the freezer pile installation (Yoshimi et al., 1984). The frozen samples were wrapped with plastic sheets to minimize sublimation of the pore ice and carried to the laboratory by a refrigerator car.

In addition to the sampling of the frozen sands, the standard penetration tests (SPT) were carried out near the sampling locations as indicated in **Fig.7**. **Figure 8** presented the profile of the SPT *N*-value at these sites.

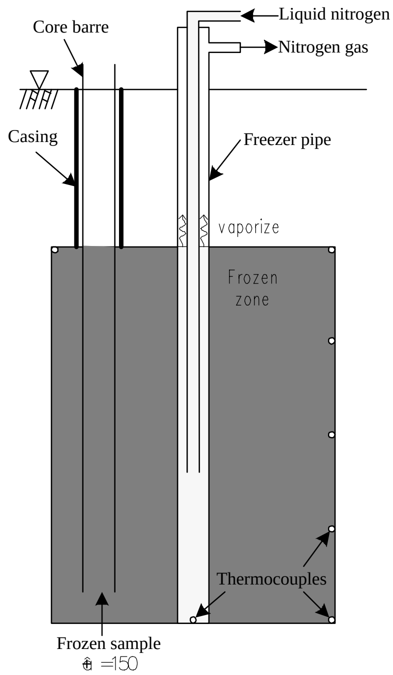

Fig.6 Schematic illustration of in-situ freezing and sampling of frozen sand

3.2 *Distribution of degree of saturation*

A total of 83 triaxial and hollow cylindrical specimens were cut out and trimmed from the frozen samples. The degrees of saturation of the specimens were measured and are plotted against depth in **Fig.9**.

Soils in natural deposits under the ground water level are usually considered to be fully saturated.

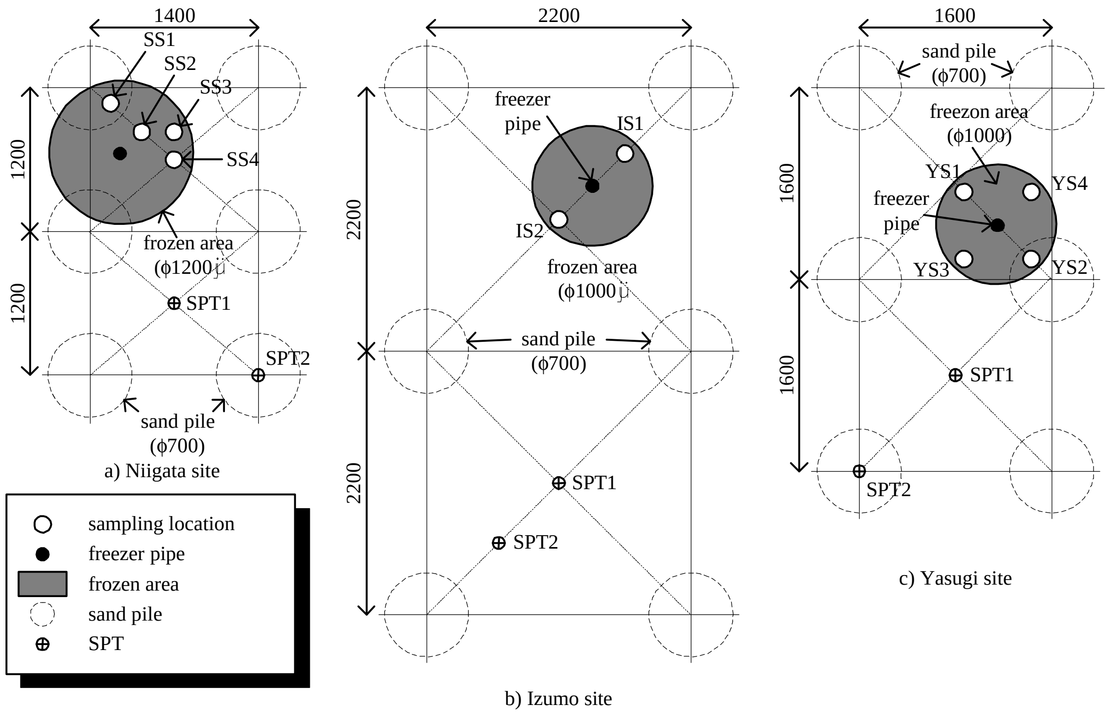

Fig.7 Locations of sampling and in-situ test in the three sites

However, specimens obtained from these three sites were not saturated, with S_r ranging between 68.8% and 96.2%. This unusually low value of S_r is believed to be due to the large amount of air exhausted in the ground during sand pile construction. There is a trend also of the decrease of the degree of saturation as the distance from the sand pile increases, but no clear trend of variation of S_r with depth can be detected.

3.3 *Undrained hollow cylindrical cyclic shear tests on unsaturated samples*

Two sets of undrained hollow cylindrical cyclic shear tests were performed to investigate liquefaction resistances of the desaturated sands taken from the Niigata site and the Izumo site. The frozen samples were cut out and trimmed in the laboratory with a steel straight edge to 100 mm high specimens, with the inner and outer diameters of 60 mm and 100 mm, respectively. In order to expel any air entrapped between the specimen and membrane, and any air in the tubes, small amounts of water was circulated before the specimens started to thaw. The back pressure equivalent to the in-situ hydrostatic pressure at the depth was applied so that air bubbles size in the specimens became the same size as that in-situ when the specimens thawed. The specimens were thawed under the drained condition, with a valve connecting the specimens and the water tank. In consideration of these procedures, the degree of

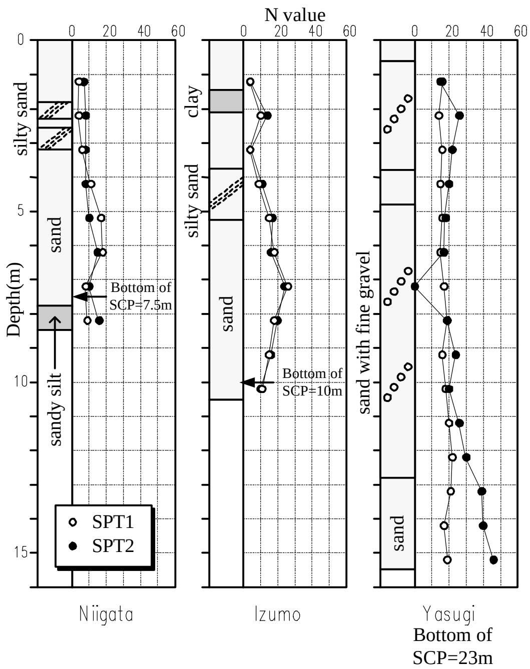

Fig.8 Distribution of the SPT *N*- value

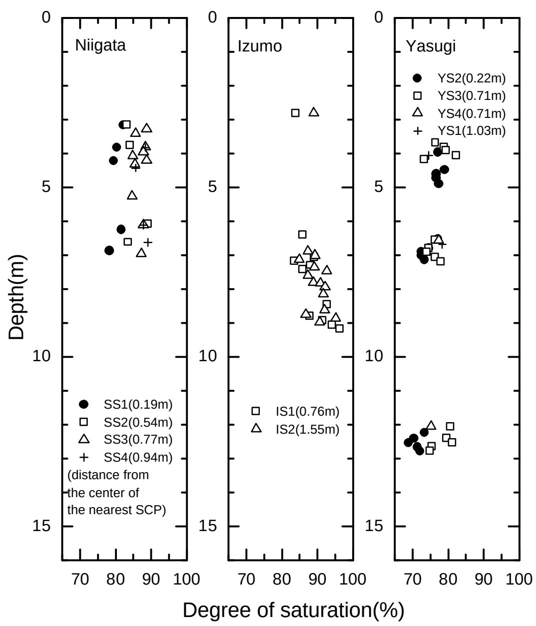

Fig.9 Distribution of degree of saturation

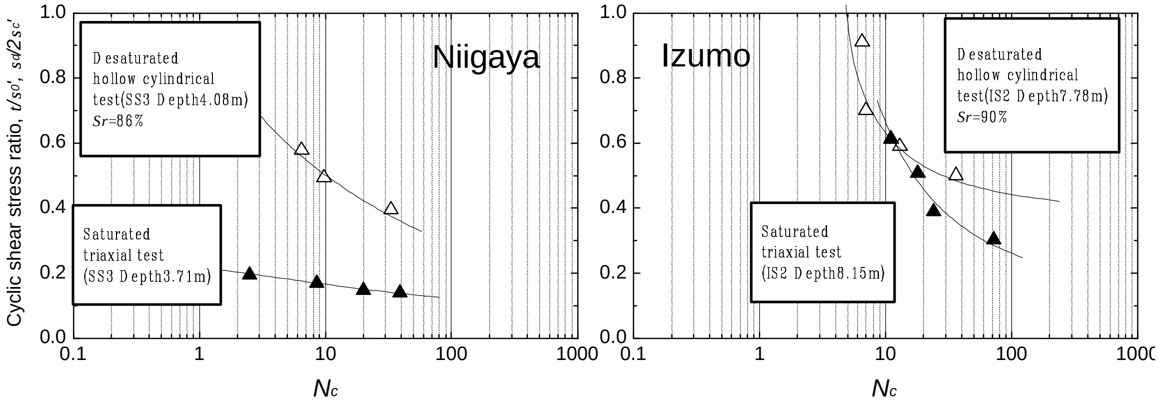

Fig.10. Relationship between cyclic stress ratio and number of cycles

saturation, S_r, of the specimens may be slightly higher than that of the in-situ ground. After the complete melting of the specimens was consolidated isotropically to the pressures approximately equal to the in-situ vertical effective pressures, the specimens were torsionally sheared with uniform amplitudes of cyclic shear stress, with the height of specimen fixed. Specimens were taken from the depth of 4.02~4.14m of the sample SS2 and specimens from the depth of 7.72~7.90m of the sample IY2. The S_r values of these specimens were about 86% and 90%, respectively.

Triaxial tests were also conducted on the specimens taken from the frozen sample. The locations of triaxial and hollow cylindrical specimens were very close to each other in the frozen samples. The triaxial specimens were fully saturated in the triaxial cell after thawing and then subjected to cyclic loadings.

Figure 10 shows relationships between the cyclic stress ratio and the number of cycles to cause a double amplitude axial strain DA= 5% in triaxial tests and DA= 7.5% in hollow cylindrical tests. The stress ratio for 20 cycles of the unsaturated specimens from SS2 was approximately twice of that compared with the saturated condition. For the case of specimens from IY2, the stress ratios were significantly higher than those in saturated condition. It can be seen in this figure that the lower the degree of saturation, the more significant the liquefaction resistances are enhanced.

Liquefaction resistances are generally estimated from *N*-value in practice (e.g. Japan Road Association, 1996). But N-value does not reflect the effect of degree of saturation on the liquefaction resistances. It can be concluded that the liquefaction resistances of the improved sand are considerably higher than those obtained from the *N*-value based conventional method which is only available for fully saturated soils.

4 CONCLUSIONS

A centrifuge test in which air was injected into saturated model ground through a vertically penetrated pile was conducted. The following results were found in the test: the area of the region where air bubble spouted from the ground surface increased with the supplied air pressure, and the area was found to be significantly wider than the typical spacing of sand piles in practice.

Undisturbed high-quality samples were obtained by the ground freezing method from three sites where the grounds were improved with SCP. The degree of saturation of the ground was found to be unusually low, in a range between 68.8 % and 92.6%. Results of hollow cylindrical undrained cyclic shear tests on the samples indicted that the resistance to liquefaction was significantly enhanced by the desaturation during SCP construction. The liquefaction resistances of the improved sand are considerably higher than those obtained from the *N*-value based conventional method which is only available for fully saturated soils.

REFERENCES:

Fudo Construction Co., Ltd. 1999. Fudo's total foundation engineering system

Japan Road Association. 1996. Specifications for highway bridges, part V, *earthquake resistant design, Maruzen*, 228p (in Japanese)

Yoshimi, Y., Hatanaka, M. and Oh-oka, H. 1978. Undisturbed sampling of saturated sands by freezing, *Soils and Foundations*, 18(3), 59-73

Yoshimi, Y., Tokimatsu, K., Kaneko, O. and Makihara, Y. 1984. Undrained cyclic shear strength of a dense Niigata sand, *Soils and Foundations*, 24(4), 131-145

Sherif, M. A., Ishibashi, I. and Tsuchiya, C. 1977. Saturation effet on initial soil liquefaction, Journal of the *Geotechnical Engineering Division*, ASCE, 103(8), 914-917

Martin, G. R., Finn, W. D. L. and Seed, H. B. 1978 Effects of system compliance on liquefaction tests, *Journal of Geotechnical Engineering Division*, ASCE, 101(5), 423-438

Yoshimi, Y., Tanaka, K. and Tokimatsu, K. 1989. Liquefaction resistance of a partially saturated sand, *Soils and Foundations*, 29(3), 157-162