Liquefaction of sands sampled by in situ freezing

Liquéfaction des sables échantillonnés par gel in situ

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SYNOPSIS High-quality undisturbed samples of saturated sands, a dense sand and a loose volcanic sand called shirasu, were obtained by freezing the sands in situ, without impeding drainage under an adequate confining pressure. The undrained cyclic strength (liquefaction resistance) of the undisturbed samples was much greater than the samples reconstituted at equal or higher densities. The method of sampling is expected to provide an effective means for evaluating the liquefaction resistance of saturated sand deposits.

INTRODUCTION

Undisturbed sampling of sand below groundwater table is one of the most difficult problems in subsurface investigations. Yet the need for it has recently increased in connection with aseismic design of earth structures and structural foundations involving probable occurrence of liquefaction or cyclic mobility, particularly for the following cases: (1) when important structures are designed for unusually strong earthquakes which may affect even dense sand, and (2) when unusual cohesionless soils are involved whose behavior may be considerably different from that of ordinary sands. In both cases one is forced to extrapolate available criteria for liquefaction that are mainly based on case histories of liquefaction and SPT N-values in ordinary, mostly loose sand deposits (e.g., Seed et al, 1983; Tokimatsu and Yoshimi, 1983).

The object of this paper is to present case histories of undisturbed sampling by in situ freezing of two saturated cohesionless soils, a dense sand and a volcanic sand locally called shirasu, and some results of undrained cyclic triaxial tests on the undisturbed samples as well as on reconstituted samples.

SAMPLING BY IN SITU FREEZING

Previous studies by Yoshimi et al (1977, 1978) and Singh et al (1982) show that high quality undisturbed samples of saturated sands can be obtained by freezing them without impeding drainage under an adequate confining pressure. Thus, if a large enough sample is obtained under such conditions by in situ freezing, and if only the part of the sample sufficiently away from a possible zone of disturbance due to drilling and insertion of a freezing pipe is used, the sample may be considered to be of high quality to such an extent that the structure of the soil in situ is preserved.

Dense Sand in Niigata City

The sampling site was located at a short distance south of the Niigata railroad station. Figs. 1(a) and (b) show the soil profile and the result of the standard penetration test (SPT) by the trip monkey method. A 75-mm hole was drilled to a depth of 10 m with a rotary drilling machine using bentonite mud, and a steel pipe 73 mm in diameter and 6 mm thick was placed in the hole with the lower end open. After plugging the bottom of the steel pipe and removing the drilling fluid from inside the pipe, a copper pipe 15.9 mm in diameter and 3.5 mm thick was placed in the steel pipe for supplying liquid nitrogen as shown in Fig. 2(a).

Liquid nitrogen was supplied from a tank lorry for about 40 hours to freeze the soil around the steel pipe to a diameter of about 60 cm, consuming about 1000 kg of liquid nitrogen per cubic meter of frozen sand. In order to recover as much frozen sample as possible, a 607-mm core barrel with hard metal teeth was lowered around

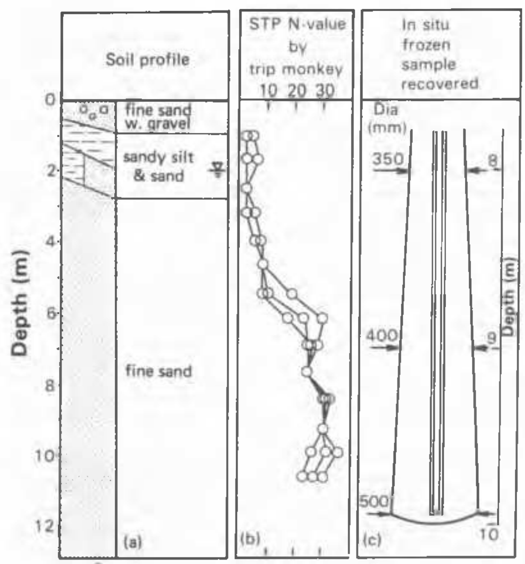

Fig.1 Soil Profile and Frozen Sample at Niigata Site

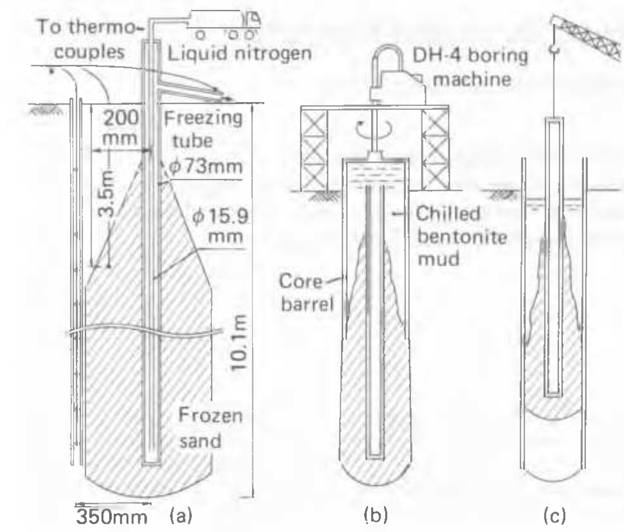

Fig.2 Schematic Drawing of Sampling Procedure at Niigata Site

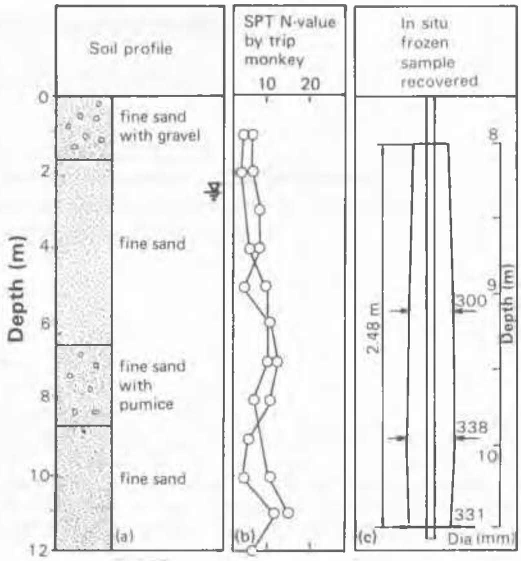

Fig.3 Soil Profile and Frozen Sample at Kagoshima Site

the frozen column of soil to a depth of 10.5 m by turning it with a boring machine using chilled bentonite mud. Although the upper part of the frozen sand melted because the temperature of the bentonite mud was not kept low enough, a good size sample of sand below a depth of about 8 m was obtained as shown in Fig. 1(c). The frozen sample was cut into blocks, wrapped in heavy vinyl sheet, and carried to the laboratory in a refrigerated truck.

Alluvial Shirasu in Kagoshima City

The sampling site was located about 1.3 km southwest of Kagoshima railroad station. Figs. 3(a) and (b) show the soil profile and the result of the SPT by the trip monkey method. In order to seek a more economical method of in situ freezing, a different method was tried by which a sample of limited length was frozen and cored as illustrated in Fig. 4 in the following manner: A 420-mm hole was drilled to a depth of 8 m with a DH-4 type boring machine, and a 406-mm steel casing was placed in the hole. In the center of the hole a 55-mm hole was drilled to a depth of 10.6 m. A steel pipe 50.8 mm in diameter and 4 mm thick to which a polyvinyl chloride (pvc) rod 50 mm in diameter and 300 mm long was fixed was placed in the 55-mm hole. Four thermocouples for monitoring the ground temperatures were attached on the surface of the pvc rod with an interval of 50 mm. The top of the steel pipe was screwed to another steel pipe 73 mm in diameter and 10 mm thick that was covered with glass wool for thermal insulation, for the dual purpose of keeping the bentonite mud from freezing and of conserving liquid nitrogen. Another steel pipe 42.7 mm in diameter and 3.5 mm thick was placed in the 73-mm pipe for additional thermal insulation.

A copper pipe 15.9 mm in diameter and 3.5 mm thick was placed in the 42.7-mm steel pipe to supply liquid nitrogen which was allowed to rise in the annular space around the copper pipe. Liquid nitrogen was supplied from a pressurerized vessel of 360-kg or 720-kg capacity for about 38 hours to freeze the soil to a diameter of about 40 cm. Unexpectedly long time for changing the vessels every 3 to 7 hours required more liquid nitrogen than would have been necessary if it had been supplied continuously from a larger vessel, e.g., a tank lorry. A total of 4000 kg of liquid nitrogen was consumed. A flow of 15°C bentonite mud was supplied in the area around the joint between the 73-mm pipe and the 50.8-mm pipe to keep the joint from freezing. The diameter of the frozen column of soil was estimated from the temperatures monitored based on the assumption that the soil below the bottom of the freezing pipe would freeze in a semi-spherical shape. When the time was ripe the inner pipes were removed, and the 73-mm pipe was then removed by unscrewing. The frozen soil was

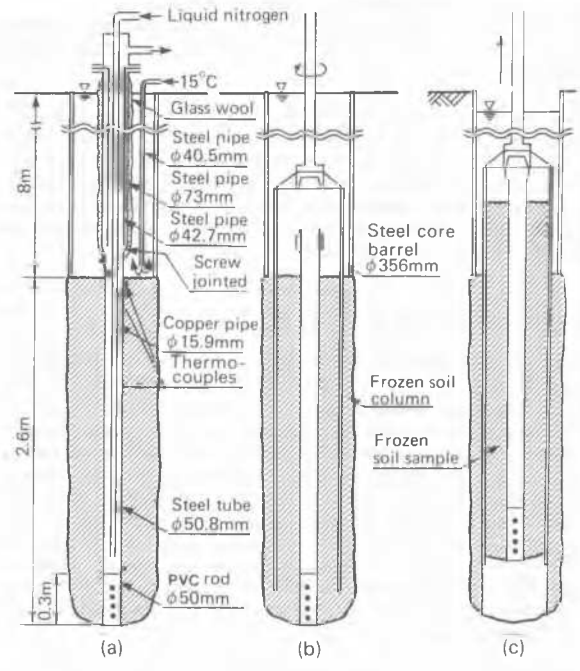

Fig.4 Schematic Drawing of Sampling Procedure at Kagoshima Site

cored with a steel core barrel 356 mm in diameter, 11 mm thick and 3.85 m long having hard metal teeth. The coring from 7.5 m to 10.7 m took about 30 min. with the DH-4 type boring machine using bentonite mud at temperatures from 10 to 15°C. The core was then lifted by gripping the freezing pipe. The core was as shown in Fig. 3(c). The frozen sample was sawed into blocks which were carefully wrapped in vinyl sheet for transportation in a refrigerated truck to the laboratory.

LABORATORY TESTS ON SOIL SAMPLES AFTER THAWING

Physical Properties of Samples Tested

Table I shows the physical properties of the samples for which undrained cyclic test results are reported in this paper. The maximum and minimum dry densities were determined by the JSSMFE Standard Method of Test for the Maximum and Minimum Densities of Sand, JSF Standard T26-81R. The physical properties of the shirasu are typical of alluvial shirasu in this region (Haruyama, 1973).

Unidirectional Freezing Tests

A series of unidirectional freezing tests similar to those by Yoshimi et al (1978) were conducted to determine critical effective stress to prevent an increase in soil volume during freezing. The test results showed that an effective stress of 50 kPa was adequate which was equivalent to the overburden stress at a depth of about 4 m. The samples shown in Table I, therefore, were under adequate confining stress to prevent expansion due to freezing.

Undrained Cyclic Triaxial Tests on the Niigata Sand

Undrained cyclic triaxial tests were conducted on undisturbed specimens prepared from the frozen sample and on some specimens reconstituted to the same density, by applying uniform sinusoidal cycles of deviator stresses at a frequency of 0.05 Hz. Cylindrical specimens of the frozen sand, 50 mm in diameter and 125 mm high, were trimmed from the frozen sample at least 10 cm away from the freezing pipe because it had been estimated that the frozen sand more than 6 cm away from the freezing pipe was free from the effect of disturbance due to the drilling and insertion of the freezing pipe (Yoshimi et al, 1984). Each frozen specimen was placed in a triaxial apparatus, covered with a rubber membrane, and thawed under an isotropic pressure of 30 kPa. After the specimen thawed completely, it was saturated until the pore pressure coefficient B-value reached 0.95 or more, and then consolidated under an isotropic stress of 98 kPa that was about equal to the effective vertical stress of the soil in situ.

The reconstituted specimens were prepared from the remainder of the frozen sample in order to study their behavior in comparison with the undisturbed specimens. Two of the methods used by Mulilis et al (1977) were adopted, i.e., the pluviation through air (PA) method and the moist tamping (MT) method. The pore air in the reconstituted specimens was replaced with CO_2 gas in order to facilitate saturation which was carried out in the same way as for the undisturbed specimens.

Fig. 5 shows the relationship between the shear stress ratio and the number of cycles to reach double amplitude axial strain (DA) of 5 %. Note the very high shear stress ratios well in excess of 1.0 which have not been seen in previously published test data on dense reconstituted specimens of sands. When compared at 20 cycles, the strengths of the PA and MT samples are only 30 % and 60 %, respectively, of that of the undisturbed sample, although the densities are about the same for all the samples.

TABLE I

Physical Properties of Soils Tested

Site	Niigata	Kagoshima
Depth (m)	9.5-9.9	9.3-9.6
Specific gravity of solids	2.68-2.70	2.42-2.58
50 % diameter (mm)	0.28-0.30	0.28-0.43
10 % diameter (mm)	0.16-0.19	0.024-0.065
Uniformity coefficient	1.7-1.9	8.2-15.3
Fines content (%)	0	11.1-17.4
Max. dry density (t/m^3)	1.51-1.53	0.96-1.08
Min. dry density (t/m^3)	1.22	0.70-0.79
Density index (%)	81-90	69-80

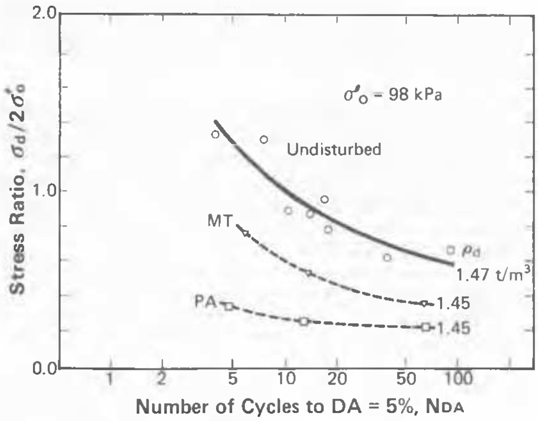

Fig.5 Undrained Cyclic Strength of Niigata Sand

Undrained Cyclic Triaxial Tests on the Kagoshima Shirasu

The apparatus and procedure of triaxial tests on the Kagoshima shirasu were the same as those for the Niigata sand except that the specimens were thawed under an isotropic stress of about 20 kPa, the cyclic stresses were applied at 0.5 Hz, and that the consolidation stress was about 1.1 times the effective overburden stress in the field. The consolidation stress was admittedly higher than the mean effective stress in the field. That was adopted, however, to ensure that the test result would not overestimate the strength in the field in the form of shear stress ratio, because the sampling and testing program was intended for application to an actual construction project.

The reconstituted specimens were prepared from the remainder of the frozen sample to study the effect of sample disturbance on the undrained cyclic shear strength. After thawing, the sample was broken up by fingers with extreme care not to crush the soil particles which were characteristically angular and fragile. The wet, remolded shirasu was poured into a water-filled mold in about 10 layers and compacted by hitting the mold with a wooden tamper 30 mm in diameter. Despite considerable efforts to reproduce the density of the undisturbed sample, the density indexes of the reconstituted specimens were about 13 percentage points higher.

Fig. 6 shows typical results of the undrained cyclic tests in the form of the relationship between the shear stress ratio and the number of cycles to cause a double amplitude axial strain of 5 %. Note that the strength of the reconstituted sample is considerably lower than the undisturbed sample (about 60 % when compared at 20 cycles), despite the fact that the former is denser than the latter. The test result suggests that the soil is sensitive to sample disturbance.

DISCUSSION

Figs. 5 and 6 show that one is likely to largely underestimate the undrained cyclic strength of dense sand or shirasu based on laboratory tests on disturbed samples. It has been shown that so-called undisturbed samples of the Niigata sand obtained by a conventional core barrel were in fact considerably disturbed (Yoshimi et al, 1984).

The method of undisturbed sampling by radial freezing using a single bore hole has successfully been tried at 9 locations in Japan including the two cases reported in this paper. Liquid nitrogen was used in all cases except one in which a mixture of ethanol and crushed dry ice was used (Yoshimi et al, 1977). A sample of shirasu was recently obtained from a depth of about 25 m using the method of Fig. 4. The application of a similar method in Italy was reported by Da Roit et al (1981).

Although the in situ freezing method may still be too expensive for routine soil investigations, the cost may be justified (1) for a very important structure, (2) for an unusual cohesionless soil as in the case of the shirasu, and (3) as a "bench mark" by which to evaluate the reliability of other less expensive methods of soil investigation.

CONCLUSIONS

The following conclusions may be drawn based on the undrained cyclic triaxial tests on undisturbed samples of a dense sand and a loose shirasu obtained by in situ freezing:

(i) The quality of the undisturbed samples obtained by the in situ freezing method was judged quite good based on the fact that requirements for preserving the structure of the soil were satisfied.

(ii) Compared with the undrained cyclic strength (liquefaction resistance) of the undisturbed samples obtained by in situ freezing, that of the reconstituted samples was about 30 to 60 %, provided that the strength was defined as the shear stress ratio required to cause a double amplitude axial strain of 5 % in 20 stress cycles.

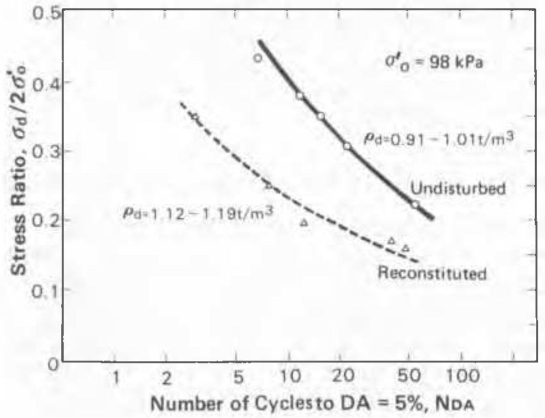

Fig.6 Undrained Cyclic Strength of Kagoshima Shirasu

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