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TWO METHODS FOR THE DETERMINATION OF LATERAL STRESS IN SAND

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ABSTRACT

Two Methods (Method A and Method B) used to determine the in-situ horizontal stress of cohesionless soil are presented. Method A is a laboratory test. In Test Method A, a high-quality undisturbed sample of cohesionless soil recovered by the in-situ freezing technique was thawed under no-lateral strain condition in a special cell under the in-situ vertical stress. The cell pressure at the time when the frozen sample was completely thawed indicates the in-situ horizontal stress. Method B is a field test. In Test Method B, a special measuring device was inserted into a frozen borehole below subsoil provided by in-situ freezing sampling. The pressure measured in the device when the surrounding subsoil was completely thawed indicates the in-situ horizontal stress. A series of comparative tests to confirm the reliability of these two proposed methods were performed in the laboratory. Sand specimens with given stress histories (overconsolidation ratio = 2, 4 and 6) were frozen one-dimensionally and then used in comparative tests. The horizontal stress in the sand specimen before freezing was directly measured for comparison. Good agreement of the horizontal stress measured with Test Method A and in the sand before freezing was measured. Good agreement of the horizontal stress measured in the Method B and in the sand before freezing was also observed. These results indicate that a freeze-thaw sequence used in this study did not change the state of stress in the sand before freezing. The results also indicated that both Test Method A and Test Method B proposed in this study are reliable for measuring the in-situ state of stress in the cohesionless soil.

Key words: at rest pressure, freezing, lateral stress, residual stress, sand, sandy soil, test equipment, test procedure, thawing (**IGC**: D4)

INTRODUCTION

The prediction of the in-situ state of stress in soil is of major importance in a wide variety of geotechnical problems. Numerous investigators have addressed this problem and have achieved varying degrees of success. Although a substantial data base has been developed, it is still not possible to predict exactly the in-situ state of stress in most natural soil deposits because they have undergone a complex-stress history of loading and unloading which is difficult to evaluate precisely. The geostatic vertical stress can be estimated from a profile of effective overburden stress with depth. The in-situ horizontal stress, however, is very much dependent on the geological history of the soil.

Three approaches to the in-situ measurement of horizontal stress, earth pressure cells, hydraulic fracturing, and self-boring devices, have been made by many investigators. The discussions of their applications are described in detail in the state-of-the-art report prepared by Ladd et al. (1977). In conclusion, although these methods have shown some degree of success in measuring the in-situ state of stress of a soft cohesive soil, no data on the sand are shown, and further development of the technique for the in-situ measurement of the horizontal stress of the cohesionless soil is required.

The object of this paper is to present two methods for the determination of in-situ lateral stress in a cohesionless soil using a high quality undisturbed sample or by making use of the frozen borehole, both of which utilize in-situ freezing sampling.

FUNDAMENTAL IDEAL OF THE TWO METHODS PROPOSED

The in-situ freezing method has been recognized as a reliable technique for obtaining high quality undisturbed samples of cohesionless soil (Yoshimi et al.(1978, 1984);

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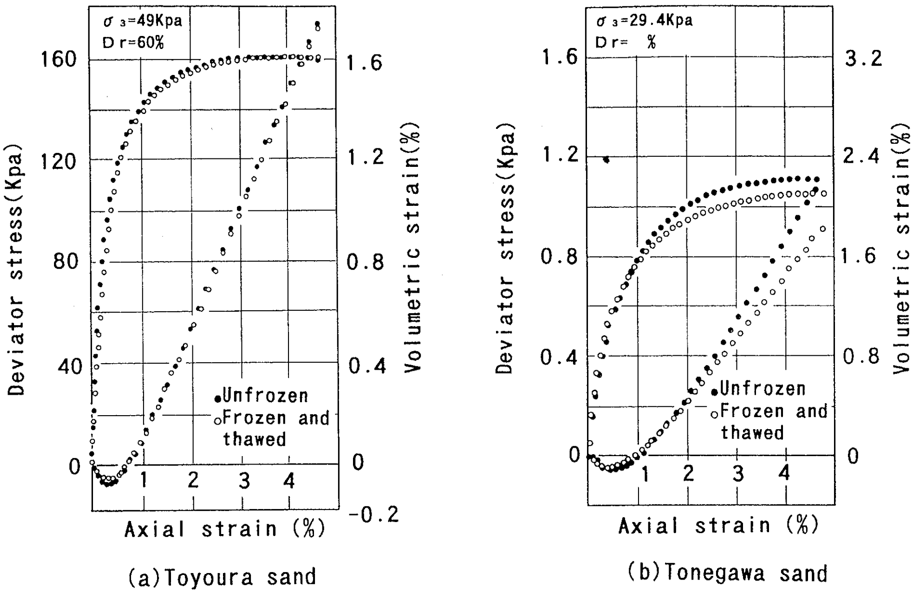

Fig. 1. Effect of freeze-thaw sequence on stress-strain and dilatancy characteristics (After Yoshimi et al., 1978)

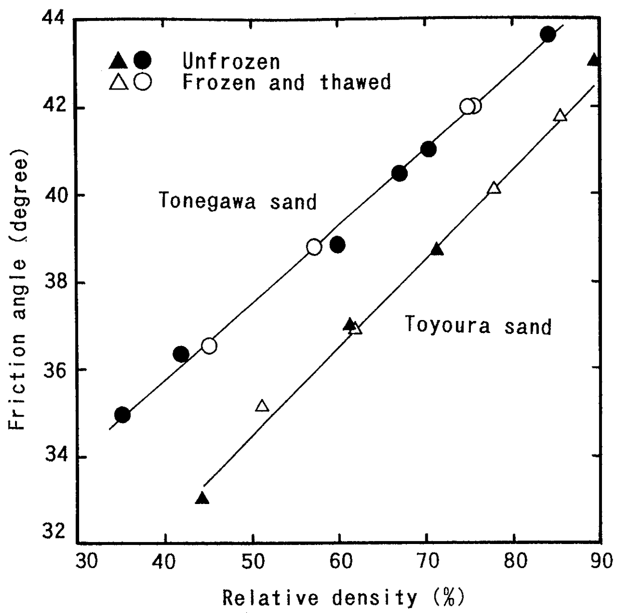

Fig. 2. Effect of freeze-thaw sequence on friction angle (After Yoshimi et al., 1978)

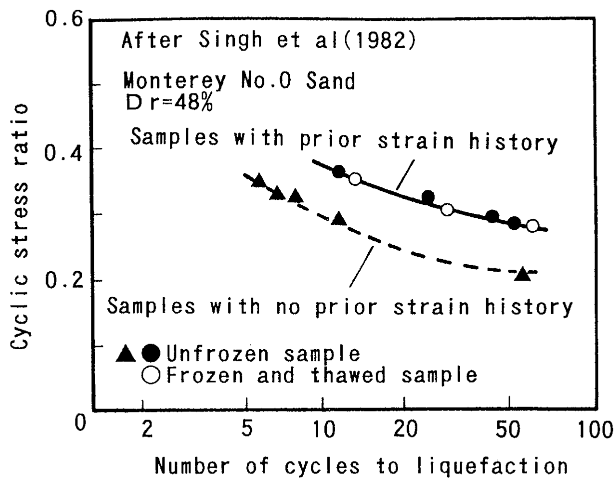

Fig. 3. Effect of freeze-thaw sequence on liquefaction strength of sand with prior strain history (After Singh et al., 1982)

Hatanaka et al. (1985, 1988)). Yoshimi et al. (1978) provided some data on the effects of a freeze-thaw cycle on the static strength and deformation characteristics of a clean sand. In Fig. 1, the solid circle indicates unfrozen samples, and the open circle shows the samples with a history of freeze and thaw sequence. No significant changes in stress-strain relationship and dilatancy characteristics were observed. In Fig. 2, the solid circle and the solid triangle show the unfrozen samples, and the open circle and open triangle indicate samples with a history of freeze and thaw sequence. No significant effect of freeze and thaw sequence on the internal friction angle of sands was observed. Singh et al. (1982) showed that a freeze-thaw sequence does not disturb the stress history of a reconstituted sample of clean sand (*see* Fig. 3). It can be seen clearly in Fig. 3 that the existence of a freeze-thaw sequence between the pre-shearing and liquefaction test does not eliminate the effect of the stress history of pre-shearing on the liquefaction strength of the sand specimen. Based on the test results, the authors proposed two methods to determine the in-situ lateral stress of the cohesionless soil by taking advantage of the in-situ freezing sampling method. These two methods are designated Methods A and B hereafter.

Method A is a laboratory test and the test apparatus is shown schematically in Fig. 4. In Test Method A, a high-quality undisturbed sample of sand, recovered with the in-situ freezing technique, was thawed in the no-lateral strain (Ko) condition in a triaxial-type cell under a vertical stress equal to the in-situ vertical effective stress at the sampling depth. The cell pressure, at a time when the frozen sample was completely thawed, indicates the in-situ lateral stress. Method B is a field test in practice. Only the laboratory test apparatus and test results, however, are described in this paper, and schematically shown in Fig. 5. The test apparatus for Method B for in-situ measurement is being developed. In Test Method B, a special measuring apparatus is inserted into a frozen borehole in model subsoil. The pressure measured in the apparatus, when the surrounding model subsoil was completely thawed under a no lateral strain condition, indicates the in-situ lateral stress before freezing. The details of the test apparatus, test procedures and the test results obtained with Method A and Method B are described below.

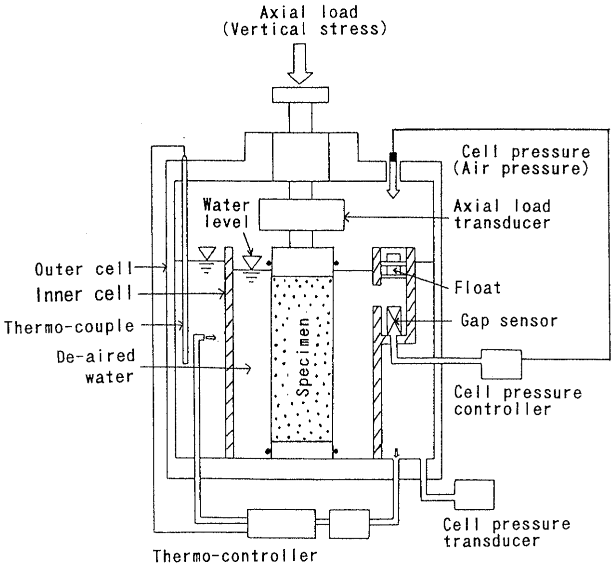

Fig. 4. Apparatus used for Test Method A

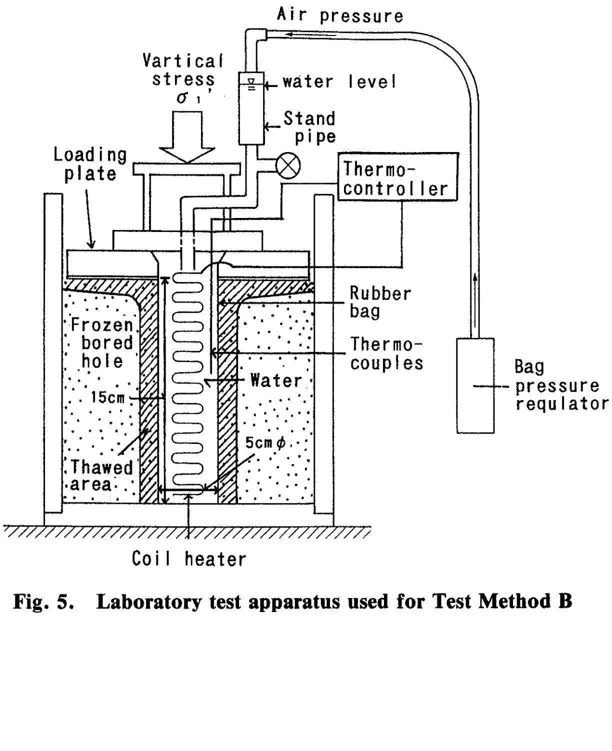

Fig. 5. Laboratory test apparatus used for Test Method B

METHOD A USING A FROZEN SAND SPECIMEN

As shown in Fig. 4, the pressure cell used in Test Method A consists of an inner cell and an outer cell. The frozen test specimen (5 cm in diameter and 10 cm in height) was placed on the pedestal. The test specimen was then covered with an impermeable rubber membrane and sealed up to the pedestal and the top cap using o-rings. The inner cell made of two half-cylinders was fixed on the base plate of the pressure cell around the test specimen. The inner cell was then filled with water to a level somewhat higher than the top surface of the test specimen. A float was placed on the surface of the water in the inner cell. A gap sensor for measuring the vertical movement of the water level in the inner cell was fixed to the inner cell at a location just below the float. The lower end of the frozen specimen was then connected to an acrylic pipe filled with water. An isotropical stress of about 9.8 kPa (0.1 kgf/cm^2) was applied in order to fasten the rubber membrane on the frozen specimen. The level of water in the inner cell under this isotropical stress was established at its initial level. The frozen specimen was then allowed to thaw in a drainable state, under an axial stress, which was the same as the effective vertical stress applied on the soil specimen in-situ before freezing.

The axial stress was applied through an axial loading rod, in stages to its final value and after reaching the final value maintained constant during thawing of the frozen specimen.

Lateral displacement of the test specimen during thawing caused a vertical movement of the water level in the inner cell. The vertical movement of the water level in the inner cell brought about a vertical movement of the float. The vertical movement of the float induced a voltage change in the gap sensor. The air pressure in the cell was then automatically adjusted to keep the water level in the inner cell constant based on the induced voltage changes. The constant water level indicated that there was no lateral strain in the test specimen during thawing of the test specimen. The air pressure therefore in the cell, at the time when the frozen test specimen was completely thawed, indicated the lateral stress in the soil before freezing.

As described above, the lateral strain in the test specimen during thawing was controlled based on the movement of the water level in the inner cell. Using this method, the volume change of the water in the inner cell due to the temperature changes greatly affected the accuracy of the test results. In order to eliminate the effects of temperature changes of the water in the inner cell, due to the heat transfer between the frozen specimen and the surrounding water in the inner cell, the temperature of the water in the inner cell was kept constant during the thawing. It is very difficult, however, to directly control the temperature of the water in the inner cell without changing the water level in the inner cell. In Test Method

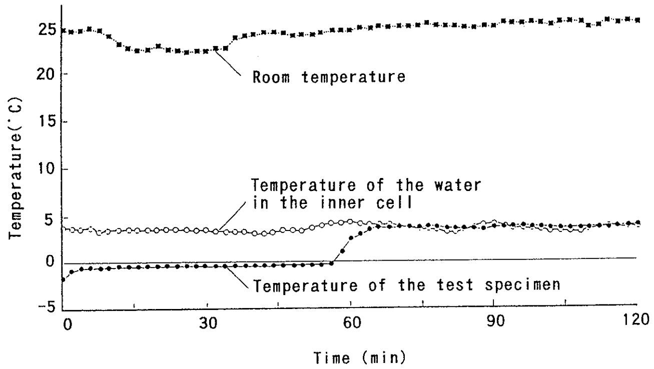

Fig. 6. Temperature control of inner cell water in Test Method A

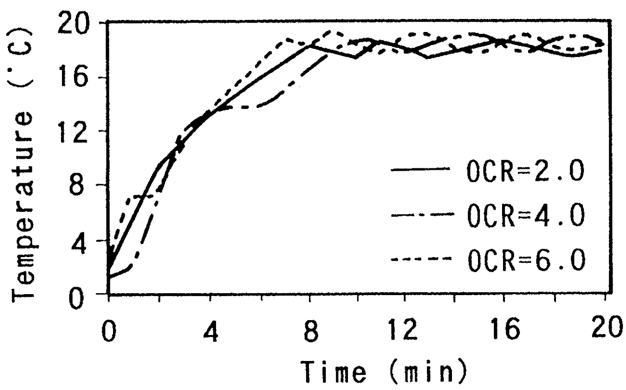

Fig. 7. Temperature control of water in the rubber bag in Test Method B

A, the temperature of the water in the inner cell was controlled as follows: The space between the inner cell and the outer cell was also filled with water at a level not higher than the inner cell. The temperature of the water between the inner cell and the outer cell was controlled so that the temperature of the water in the inner cell could be maintained constant during the thawing of the frozen specimen. In order to facilitate the temperature control, one half-cylinder of the inner cell was made of bronze. The heat transfer between the water in the inner cell and the water outside the inner cell could then be controlled more easily through this bronze half-cylinder. While the other half of the inner cell was made of transparent plastic, whereby the setup of the gap sensor and a float could be inspected from the outside of the inner cell. The temperature of the water outside the inner cell was regulated by a thermo-controller. Figure 6 shows a typical time history of the temperature of the water in the inner cell. The temperature of the water in the inner cell was controlled sufficiently throughout the thawing process of the frozen sand column. The effect of the volume change induced by the changes of the temperature of the water in the inner cell was therefore negligible. It can also be seen that the frozen specimen was thawed in about one hour.

METHOD B USING A FROZEN BORE HOLE

As described previously, Method B is a practical field test. For this paper, however, only a miniature apparatus used in the laboratory for comparative tests with Test Method A is described. The laboratory test apparatus it should be noted has particularly the same system and function as the in-situ test probe.

As shown in Fig. 5, the apparatus used for the Method B testing in the laboratory in comparative tests consists of a rubber bag, a standpipe, a bag pressure regulator and a thermo-controller. The rubber bag, about 5 cm in diameter and 15 cm in height, is fastened to the loading plate with a transparent plastic standpipe. The bag is then filled with de-aired water to a certain height of the pipe; and then installed into the frozen borehole (frozen model soil with a borehole). An initial air pressure of about 9.8 kPa (0.1 kgf/cm^2) was applied to the water in the rubber bag in order for it to adhere to the inside surface of the frozen borehole and, to measure the lateral stress in the sand accurately.

A vertical stress, which is the same as that used during the one-dimensional freezing for preparation of model subsoil in the laboratory (in case of a field test, which means the in-situ vertical stress at the depth of the frozen borehole), is reloaded on the frozen model subsoil. The frozen model subsoil with the borehole is then allowed to thaw under a drained and no-lateral strain condition, keeping the vertical stress constant. The displacement of the frozen borehole in the horizontal direction during thawing can be measured as a movement of the water level in the standpipe. The air pressure is manually adjusted to maintain a constant of the water level in the standpipe, whereby the model subsoil can be thawed under no lateral strain condition.

For the same reason mentioned for Method A, a coil heater is installed in the rubber bag in order to maintain the temperature of the water in the rubber bag constant during thawing. The coil heater is controlled automatically by a thermo-controller.

Figure 7 shows examples of the time history for the water temperature in the rubber bag during the thawing of the frozen borehole. As shown in Fig. 7, the temperature of the water in the rubber bag is controlled in the range of 18±1°C, only 8 to 10 minutes after the beginning of the frozen borehole's thawing.

LABORATORY TESTS FOR STUDYING THE RELIABILITY OF THE TWO PROPOSED METHODS

Because in-situ soils have a wide variety of unknown stress history, it is inconvenient for confirming the reliability of the proposed two methods to use an in-situ soil sample or by performing field tests. In the present study, a series of comparative tests was performed in the laboratory for this purpose. In the comparative test, considering the fact that in-situ soil has a wide variety of stress history, three sand specimens with different stress histories were used for Test Method A and also in Test

Method B. The overconsolidation ratio (OCR) of the three sand specimens was 2, 4 and 6, respectively.

Sample Preparation for Laboratory Comparative Tests

Test specimens used for the comparative tests were made of a clean sand from Toyoura. Figure 8 shows the soil gradation of the Toyoura sand. The specific gravity of the solids is 2.65, and the mean diameter is 0.195 mm and the fines content is 0.2%.

Figure 9(a) shows the schematic cross section of the container for the preparation of the frozen specimens used in the comparative tests. This container, 285 mm inside diameter and 200 mm in height, consists of a plastic cylinder, 15 mm in thickness, and a steel bottom plate. The side wall, made of plastic cylinder, is used as insulation to facilitate one-dimensional freezing (in the vertical direction) of the saturated sand specimen. The maximum radial strain of the container is smaller than 10^{-4} for the vertical load application used in the present study. Four earth pressure transducers were mounted on the side wall of the cylindrical container to measure the horizontal stress induced in the sand by a vertical load and then unloading. The earth pressure transducers have a full range of 98 kPa (1.0 kgf/cm^2) with a diaphragm 1.2 cm in diameter. The vertical load was applied pneumatically.

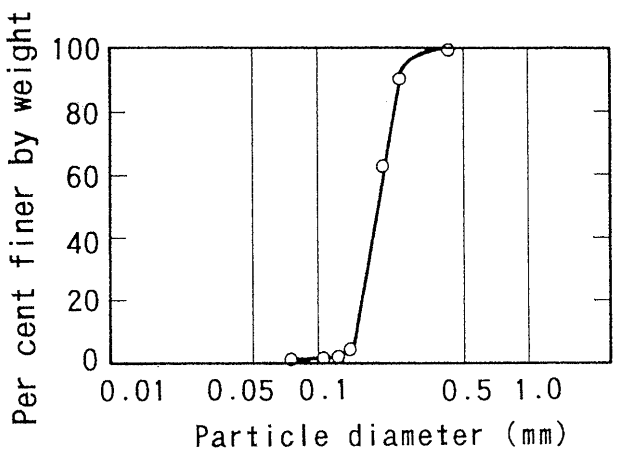

Fig. 8. Grain size distribution of Toyoura sand

The methods of sample preparations are schematically shown in Fig. 9 and are described in detail below.

(1) Dry Toyoura sand placed in the container was loaded vertically and unloaded to produce a specified stress history (Fig. 9(a)). The induced horizontal stress was measured during the vertical load application. Figures 10(a), (b) and (c) show the relationships between the applied vertical stress and the resultant horizontal stress obtained in one-dimensional loading and unloading for a specimen having an overconsolidation ratio of 2, 4 and 6, respectively. In the present study, the overconsolidation ratio (OCR) was defined as the ratio between the maximum effective vertical stress in the vergin loading process and the effective vertical stress during the final stage of unloading. The K_0 value, the ratio between the horizontal stress and the vertical stress, obtained in the virgin loading process as shown in Figs. 10(a), (b) and (c) ranges from 0.37 to 0.39. These K_0 values are in good agreement with a value of 0.38 which was calculated from equation (1) proposed by Jaky (1948), using an internal friction angle $\phi_d=38.1°$.

The value of 38.1° is obtained from a series of drained tri-axial compression tests on Toyoura sand. As shown in Figs. 10(a), (b) and (c), three specimens were unloaded to have an OCR of 2, 4 and 6 at the final stage of stress application, respectively. After the load applications, the specimens were saturated with water (Fig. 9(a)).

$$K_0=1-\sin\phi_d \tag{1}$$

(2) One-dimensional freezing of the sand specimen

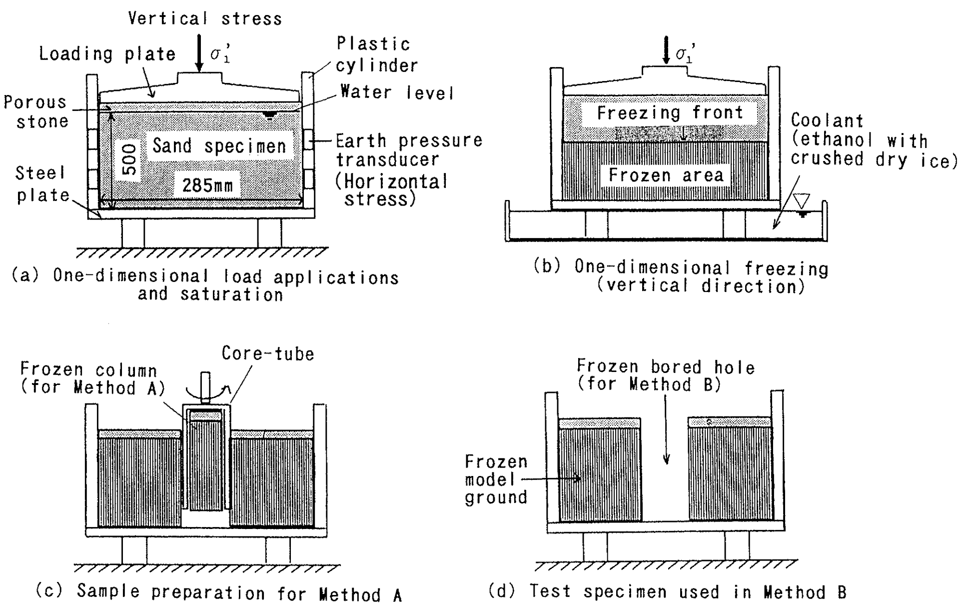

Fig. 9. Sample preparations for comparative tests

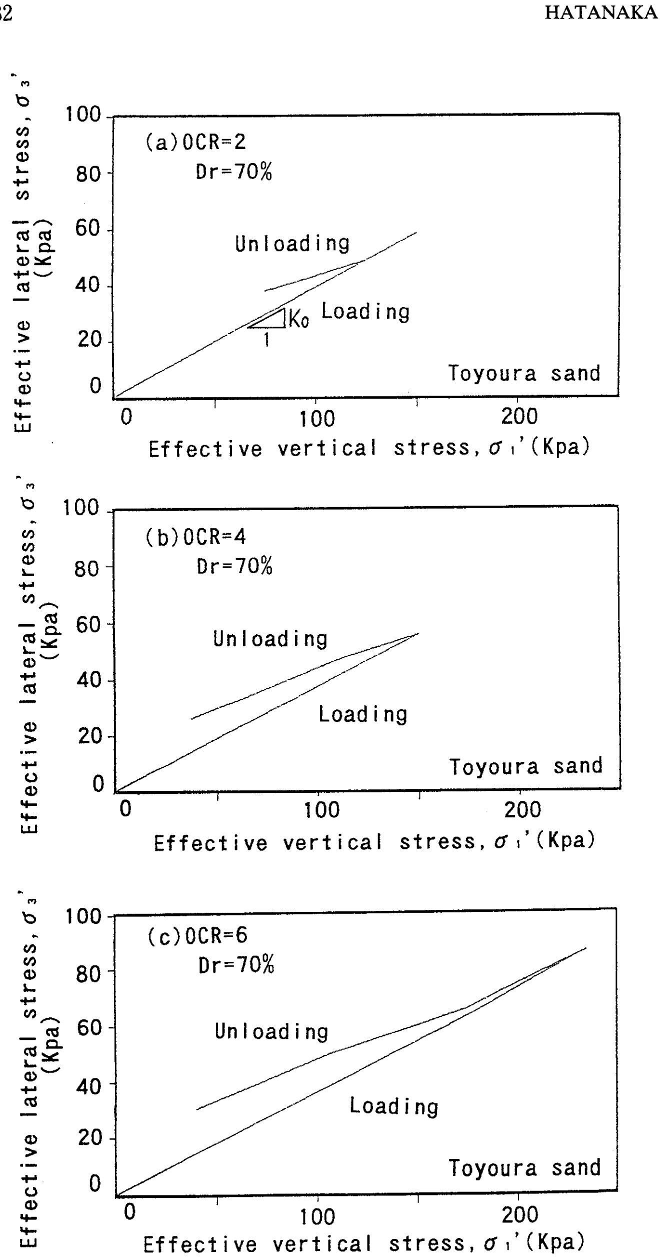

Fig. 10. Test results of one-dimensional loading and unloading on dry sand

with a given stress history is done using a coolant of ethanole and a crushed dry ice mixture, keeping the applied vertical stress constant (Fig. 9(b)). The excess pore water, due to the volume expansion of the pore water caused by freezing, is allowed to drain from the freezing face.

(3) After freezing of the saturated sand was completed, the vertical load was rebound and the loading plate was removed. A frozen sand column (5 cm in diameter) was cored from the center of the frozen model subsoil of sand using a core-tube (*see* Fig. 9(c)). The frozen sand column was then cut to a length of 10 cm to be used as a specimen in the testing of Method A. The remainder of the frozen model subsoil of sand, with a borehole in its center, was used as a test specimen for the testing of Method B (*see* Fig. 9(d)).

Unlike the measurements in the field, the horizontal stress in the model sandy subsoil before freezing was measured directly in the present study. The reliability of the proposed two methods was confirmed by comparing the horizontal stress measured in each of the Method, A and B with that before freezing. The proposed two methods could also be cross checked by comparing the measured value of horizontal stress obtained from Method A and Method B.

Comparative Test Results

a. Test results of Method A

The solid circles shown in Figs. 11(a), (b) and (c) indicate the time history of the cell pressure (σ_3') during the thawing of the frozen sand specimen with an overconsolidation ratio of 2, 4 and 6, respectively. The cell pressure increases gradually from the initial isotropical stress of about 9.8 kPa (0.1 kgf/cm^2) and approaches a certain value when the frozen specimen is completely thawed. These curves have a similar shape regardless of the overconsolidation ratio of the test specimen. As shown in Fig. 11, the cell pressure at the time when the frozen speci-

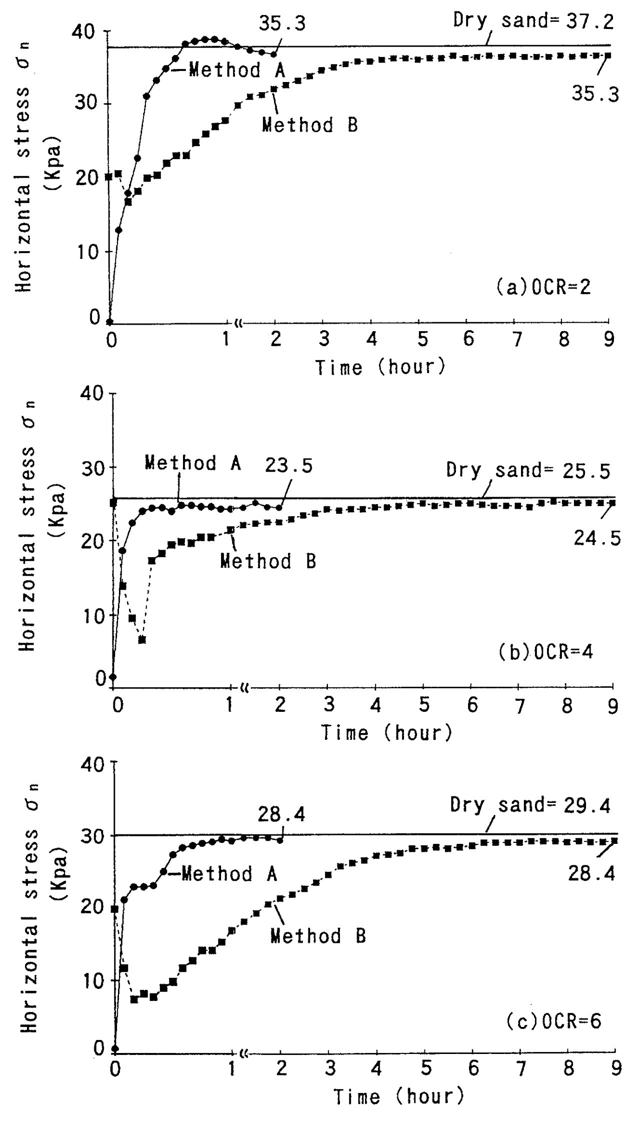

Fig. 11. Comparative test results on specimens with OCR=2, 4 and 6

men is fully thawed is 35.3, 23.5 and 28.4 kPa (0.36, 0.24 and 0.29 kgf/cm^2) for the test specimen having an overconsolidation ratio of 2, 4 and 6, respectively. These values are in good agreement with the lateral stress observed in one-dimensional load applications on the dry sand before freezing. These results indicate that a freeze-thaw sequence does not change the state of the stress in the sand before freezing. The results also indicate that Test Method A, proposed in the present study, is available for measuring the in-situ state of stress in the sands.

b. Test results of Method B

The solid square shown in Fig. 11 indicates the time history of the water pressure (=horizontal stress, σ_3') in the rubber bag during the thawing of the frozen borehole observed in Test Method B. A similar tendency of the time history of the water pressure in the rubber bag can be seen for all the specimens tested. In the first stage of thawing, about 8 to 10 minutes after it begins, the water pressure in the bag decreases to a certain value. This result corresponds to the rapid increase of water temperature during that time as shown in Fig. 7. This rapid increase of water temperature in the rubber bag produces rapid thawing of the inside surface of the frozen borehole adjacent to the rubber bag. As widely known, there is about a 9% volume decrease when the ice is thawing. Unfortunately, in laboratory tests, in the first period of thawing for the testing of Method B, no water can be supplied from outside the test specimen to the area of thawing, because the outside of the test specimen is still frozen in this period as shown in Fig. 5.

The volume decrease of the ice due to the phase change from ice to water therefore allows the rubber bag to expand. The expansion of the rubber bag results in a lowered water level in the standpipe.

In order to maintain a constant level of water in the standpipe, the air pressure must be reduced. Eight to ten minutes after the thawing begins, the water temperature in the bag is controlled well enough at nearly 18 degree C as shown in the Fig. 7. At that time, the frozen borehole is thought to be thawed in the hatched area as shown in Fig. 5. The water can be supplied from outside for the compensation of the volume decrease due to thawing of the ice in the sand. The rigidity of the frozen borehole decrease corresponds with the amount of actual thawing achieved. The test specimen therefore is allowed to deform in the lateral direction towards the rubber bag under the application of vertical stress. In order to maintain a constant water level in the standpipe, the pressure in the bag must be increased. After 8 to 10 minutes, the water pressure in the bag increases gradually, and it approaches a certain value, when the frozen borehole is fully thawed. As shown in Fig. 7, the temperature of the water in the rubber bag is well under control 8 to 10 minutes after the thawing begins, and this increase in water pressure is shown in Figs. 11(a), (b) and (c) indicating that an increase in the pressure is required to maintain a condition of no-lateral strain during the thawing of the frozen borehole.

As shown in Fig. 11, the bag pressure at the time when the frozen model subsoil is fully thawed is 35.3, 24.5 and 28.4 kPa (0.36, 0.25 and 0.29 kgf/cm^2) for a test specimen having the overconsolidation ratio of 2, 4 and 6, respectively. These values are also in good agreement with the lateral stress observed in the one-dimensional load applications on dry sand before freezing. These results again indicate that a freeze thaw sequence of the model subsoil will not change the state of stress in the sand before freezing. The results also show that the Test Method B is also available for measuring the in-situ state of the stress in the sand.

DISCUSSIONS ON THE LATERAL STRESS OBTAINED FROM THE TWO PROPOSED METHODS

The lateral stress observed, at the time when the frozen specimen is fully thawed, is observed from Fig. 11 in the testing of Methods A and B, and is summarized in Table 1. Also shown in Table 1 are the lateral stresses obtained at the end of one-dimensional compression on dry sand as shown in Fig. 10.

As shown in Table 1, the values of lateral stress, obtained from two independent methods proposed in the present study, are in close agreement with each other. This means that these two methods have the same degree of accuracy for the measurement of lateral stress. These values are also in good agreement with that which is measured directly on the dry sand in the one-dimensional compression tests before freezing. These results indicate that there is no significant effect of the freeze-thaw sequence on the state of stress in the sand, so long as the freezing is performed one-dimensionally without impeding the drainage.

Based on these discussions, the two methods proposed here are found to be useful for the determination of in-situ lateral stress in the sand.

If the vertical stress and the pore water pressure in-situ can be estimated, in many cases, the coefficient of earth pressure at rest, K_0, which is defined as a ratio of the effective lateral stress and the effective vertical stress, can also be obtained.

CONCLUSIONS

The following conclusions may be drawn based on the laboratory test results;

(1) Method A, by thawing a frozen high-quality undisturbed sand specimen under a condition of no lateral

Table 1. Comparisons of the horizontal stress measured from Method A, Method B and dry sand before freezing

OCR	Dry sand	Method A	Method B
2	0.38	0.36	0.36
4	0.30	0.29	0.29
6	0.26	0.24	0.25

strain in a special cell, was found to be a useful laboratory test method to determine the in-situ lateral stress of sand.

(2) Method B, by thawing the frozen borehole of sand under a condition of no lateral strain shown in the present study, was found to be an available in-situ test method to determine the in-situ lateral stress of sand. More effort should be undertaken however to develop an in-situ test probe for Method B.

(3) Laboratory test results show that the state of stress in the sand is not affected by a one-dimensional freezing and thawing sequence. This result supports the assumption that a high quality undisturbed sample of cohesionless soil can be obtained using the in-situ freezing sampling method.

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