玉砂利を使用したオープンケーソンに作用する周面摩擦に関する研究（Ⅲ）

Research on the skin Friction of open caisson using the gravel （Ⅲ）

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Abstract

Caissons or laterally loaded piers are widely used in marine constructions where loads are heavy, to support traffic poles and bridges to resist large lateral loads, and to support transmission line towers to resist large uplifting forces. The space system caisson (SS caisson) method, which is the operation method of constructing caisson foundation, is classified into open caisson construction method. In SS caisson method, space gravel is filled between caisson wall surface and soil. A detailed laboratory investigation was undertaken to study friction behavior of SS caisson. Friction between caisson wall surface and soil is reduced by the space gravel. Effects of density, water content, and penetration speed of caisson model were studied due to axial compression load. Observed results agreed well with those available in the literature. These results also indicated that small scale laboratory tests conducted in controlled conditions allow rapid and reliable information on field performance of SS caisson.

Key Words: space system caisson, skin friction, density, laboratory investigation.

1. Introduction

The analysis and investigation of skin friction of soils, which are much less homogeneous materials, is obviously still complicated (Potyondy, 1961)[1]. In constructions of caissons, many sinking difficulties occur because caissons are too light to overcome the skin friction of the ground in contact with sides. Caissons are broadly classified into pneumatic caissons and open caissons. The space system caisson (SS caisson) method, which is the operation method of constructing caisson foundation is classified into open caisson construction method. In SS caisson method, space gravel is filled between caisson wall surface and soil to provide the space. It is possible to make caisson sinking with no external loading as friction between soil and caisson is decreased by the space gravel. Detailed laboratory investigations were conducted using scale down caisson models to study skin friction behavior.

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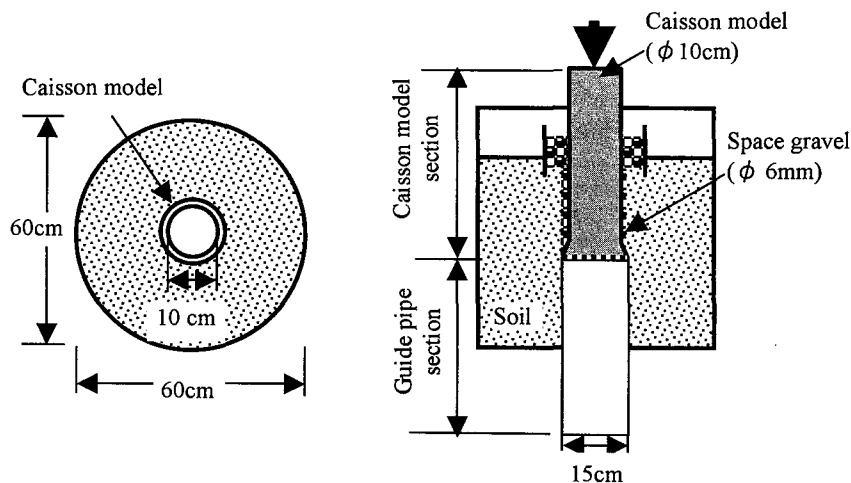　TEL0429-85-5655　FAX0429-85-5179
　E-mail：moka@nissan-con.co.jp
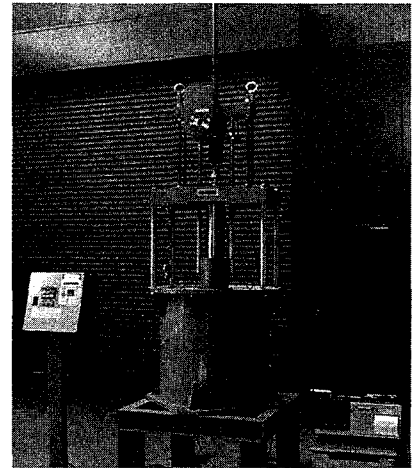
Fig. 1 Schematic diagram of experiment

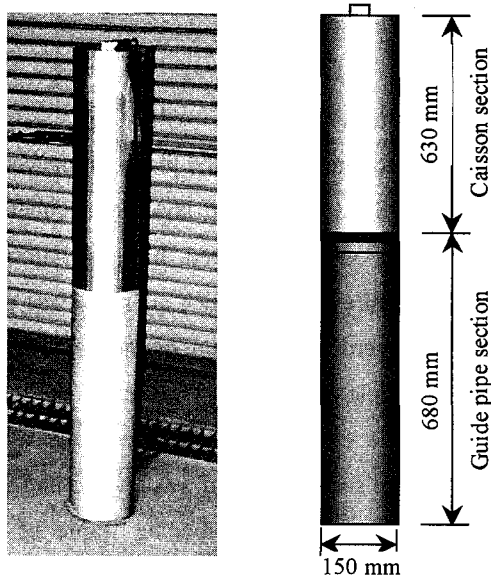Fig. 2 Photo of experiment setup

Fig. 3 (a) Photo and schematic diagram
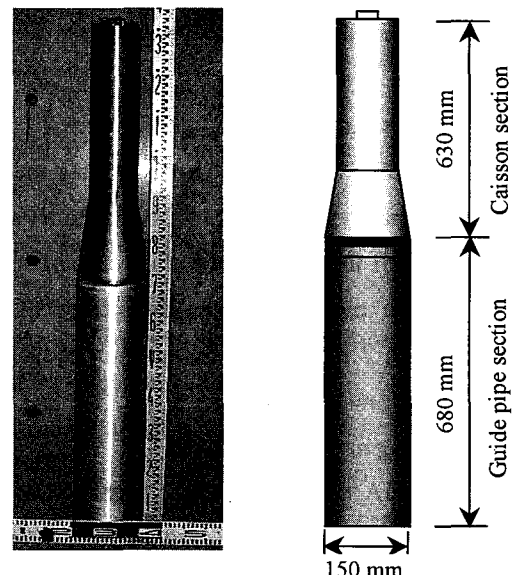of caisson model (I)

Fig. 3 (b) Photo and schematic diagram
of caisson model (II)

1. Introduction

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soil to provide the space. It is possible to make caisson sinking with no external loading as friction between soil and caisson is decreased by the space gravel. Detailed laboratory investigations were conducted using scale down caisson models to study skin friction behavior.

2. Experimental Investigations

The loading tests were performed on caisson models installed in sand in a laboratory setup. Silica ceramic balls (Space gravel) are filled continuously between caisson wall surface and sand from start to end of test. The schematic diagram of experiment and the photo of over all setup are shown in Fig.1 and Fig.2, respectively.

General test setup included four major components:

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having a diameter of 150 mm and depth of 680 mm is the guide pipe section and the upper 630 mm depth with a diameter of 100 mm at top and 150 mm at bottom is the caisson section (Fig.3 (b)).

2.2 Steel tank

A cylindrical steel tank of 600 mm diameter and 700 mm height made of 10 mm thick mild steel plates, fixed by bolts and nuts arrangement to the angle iron frame of the same dimensions, was used. Four pressure cells are installed at the tank; two of them are located at side and the other two are at the bottom of the steel tank. Soil pressures under and adjacent to the caisson model were measured by these pressure cells along with applied load.

2.3 Loading arrangement

The loading arrangement had a driving motor and a 5 kN capacity load cell. Caisson model can be penetrated into the soil sample at a constant speed by means of the motor. The penetration speed can be changed from 2 mm/min to 50 mm/min by using this loading arrangement.

2.4 Recording arrangement

TDS-601A static data logger was used to record the experiment data. The two load cells (one at loading frame and other one at inside the caisson model), and the four pressure cells (two at side and other two at bottom of the steel tank) were connected to the data logger. The load cell at loading frame gave the total resistance force from the whole caisson model and the load cell inside the caisson model gives the resistance from guide pipe section. The data logger recorded all the readings at constant time intervals.

2.5 Soil sample

Sand was used as soil medium in these tests since its behavior is free from time effects; densities are reproducible in the laboratory, and due to its easiness in handling. Air-dry Ooigawa sand without any treatment was used due to its immediately availability, keeping in view the high volume of sand necessary for the tests. Physical properties of the sand are shown in table 1.

Table 1. Properties of sand tested

Sand	Ooigawa
Minimum void ratio	0.477
Maximum void ratio	0.826
10 % size, D_{10} (mm)	0.19
60 % size, D_{60} (mm)	1.13
Uniformity coefficient	5.87
Specific gravity	2.63
Dry density (g/cm^3)	1.5
Angle of internal friction	35
Water content (%)	0.6

3. Experimental Procedure

The caisson model was first placed at the center of the chamber. Sand was placed into the chamber using rain technique and compacted by rod hammer to achieve the desire density. Much attention was paid to maintain the vertical alignment of the caisson model during the sample preparation. The same procedure was used to fill the chamber of known volume with the same sand. The surface of sand was leveled and the top cover plate was placed. A loading frame of 5 kN capacity was placed and fixed to the caisson model. Silica ceramic balls were placed on the cover plate around the caisson model. Vertical load was applied to the caisson during the test and the load cell from the loading frame measured the resistance from the whole caisson model. The load cell inside the caisson model read the resistance and skin frictional force of the guide pipe section. The difference between these forces gave the friction force of caisson model section. Friction stress was calculated by dividing that friction force with the corresponding surface area of the caisson model section.

4. Test Results and Discussion

The loading tests were performed on model caissons installed in dry sand in a laboratory setup. Test

Table 2. Test configurations

Caisson Model	Relative Density, Dr (%)	Water Content (%)	Shear Speed (mm/min)
(I)	37	4.5	10
	61	4.5	10
	83	4.5	10
	93	4.5	10
(II)	37	4.5	10
	61	4.5	10
	83	4.5	10
	93	4.5	10
	61	2.5	10
	61	3.3	10
	61	4.6	10
	61	7.5	10
	58	4.5	2
	58	4.5	10
	58	4.5	30

Fig. 4 Accuracy check of the equipment

configuration is shown in table 2. The two model caissons (mentioned above) were used in this study. Relative density, water content of soil, and shear speed of the caisson model were chosen as variables in the present laboratory investigation, due to their influence on caissons behavior under loading. Four relative densities, four water contents of soil, and three penetration speeds were chosen for the tests in this study. Space gravel was not used in tests with caisson model (I). It represented a normal caisson and the caisson outer surface directly contacts with soil. It measures the friction between the soil and the caisson model. On the other hand, caisson model (II) represents the space system caisson (SS Caisson) and the space gravel was filled between the caisson outer surface and the soil. In this case, it measures the friction between the space gravel and the caisson model. The results presented in this study pertain to the axial loading (downward) tests only, which is similar to the actual operating direction of caisson.
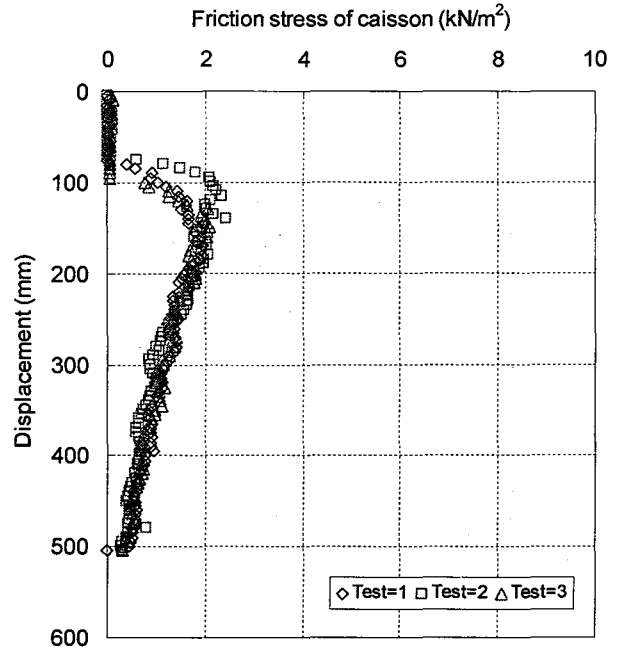
4.1 Checking the accuracy of the equipment

Before applying the equipment for the actual measurement, accuracy of the measurement of the equipment was checked using caisson model (II) for space system caisson. The three experiments for accuracy check were performed under same conditions. The relative density, water content, and shear speed in these tests were 61%, 4.5%, and 10 mm/min respectively. The results of accuracy check were shown in Fig.4. It was found that the results measured by the equipment showed well agree.

4.2 Experimental Results with Normal Caisson (Caisson Model (I))

Four experiments were performed with caisson model (I) at different relative densities (37%, 61%, 83%, and 93%), but the same water content and shear speed were used to study the behavior of friction under different densities. Fig.5 shows the friction stress of the caisson model section. Fig.5 illustrates clearly that, as expected, friction stress increased as density increased. Similar increases in friction with increasing relative
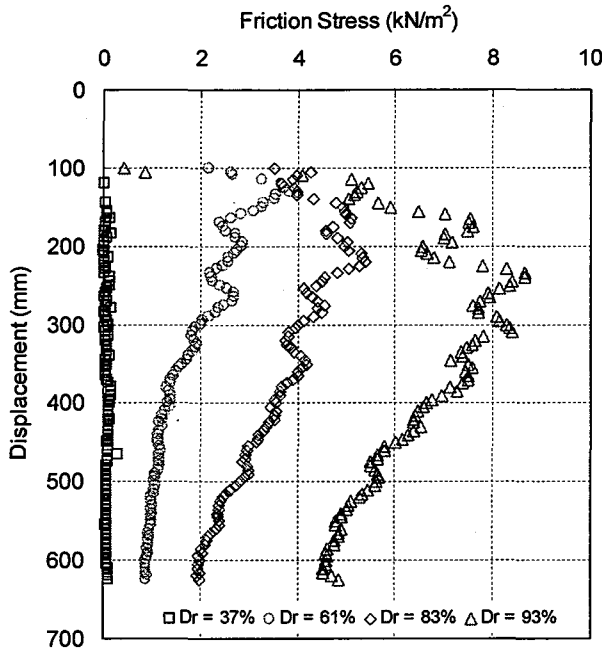
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Fig. 5 Friction stress distribution of caisson model section (Normal caisson)

Fig. 6 Distribution of horizontal earth pressure on normal caisson

density has been observed by Yalcin B. Acar et al. (1982) with sand and construction materials such as steel, wood and concrete.

Moreover, the intensity of the friction stress is low near the ground surface where the normal pressure between the caisson and soil may be expected to be small. Friction stress increases linearly up to a certain depth and then it becomes roughly constant as caisson depth increases. This behavior is clearly seen at low relative densities. The same behavior may also be expected at relatively high densities. This cannot be clearly seen in Fig.5 because of the limitation of model caisson penetration length in the laboratory setup. Many test piles in sand have been instrumented to determine the variations of axial load with depth (e.g. Vesic 1970). Two instrumented field piles were installed in sand by Lehane et al. (1993). They have concluded about the shaft shear stress in their main features of the recorded data during installation that the average shaft shear stress developed over the full shaft length increases linearly with depth up to certain penetration (2 meter in their tests), but thereafter remains roughly
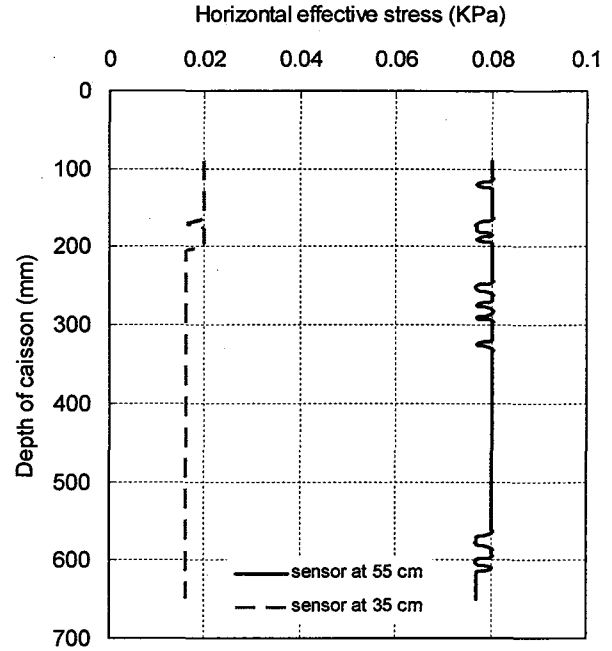
constant. The unit shaft resistance for drilled shaft (caisson) into a sand deposits is often taken, for design purposes, to increase with penetration but only up to a limiting value. O' Neill and Reese (1978) suggest an upper limiting value of unit side resistance of 0.2 MPa, and in addition propose that the unit side resistance should be considered constant for depths below 26 metre (Terzaghi and Peck "Soil Mechanics in Engineering Practice" 1996).

If the unit shaft resistance increases linearly with depth, the shaft resistance increases linearly with the shaft length (penetration), and the capacity increases with the square of the shaft length. The distribution of shaft friction was more parabolic in shape than triangular; the shaft resistance increased more rapidly near the surface than at depth (Fig.5). Others (Vesic 1970, Das and Seeley 1975) have also observed similar trends in the distribution of average shaft friction for both driven and jacked-in-place pile (Kraft 1991). Horizontal effective stresses were measured by the two pressure sensors located at the sides of the steel tank. Fig.6 shows the variation of horizontal effective
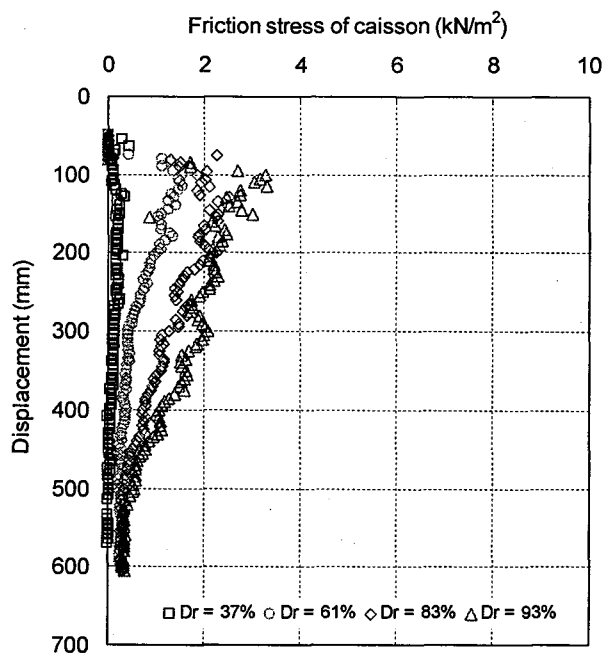
Friction stress of caisson (kN/m^2)

Fig. 7 Friction stress distribution of caisson model
section (SS caisson)

Horizontal soil pressure (KPa)

Fig. 8 Distribution of horizontal earth pressure
on SS caisson

stresses with depth of the caisson for the case of relative density 93%. While performing the experiment, guide pipe section led the caisson model section into the soil sample. This means that when the experiment started, the guide pipe section first passed through the soil sample and then the caisson model section followed. There may be possible that moving down of the guide pipe section relieves lateral stresses in the soil sample.

The construction process of drilled shaft relieves lateral stresses in the ground, where as pile driving increases these stresses. Therefore, the K/Ko ratio for shafts will be lower; where K is the ratio of the lateral effective stress to effective overburden stress and Ko is the earth pressure coefficient at rest. (Donald P. Coduto 1994 "Foundation Design Principle and Practice")

4.3 Experimental Results with SS Caisson (Caisson Model (II))

Laboratory investigations were done with space system caisson model, caisson model (II). The experiments were performed at four different relative densities (such as 37%, 61%, 83%, and 93%), but the same water content and shear speed were used to study the friction behavior at different densities. And also
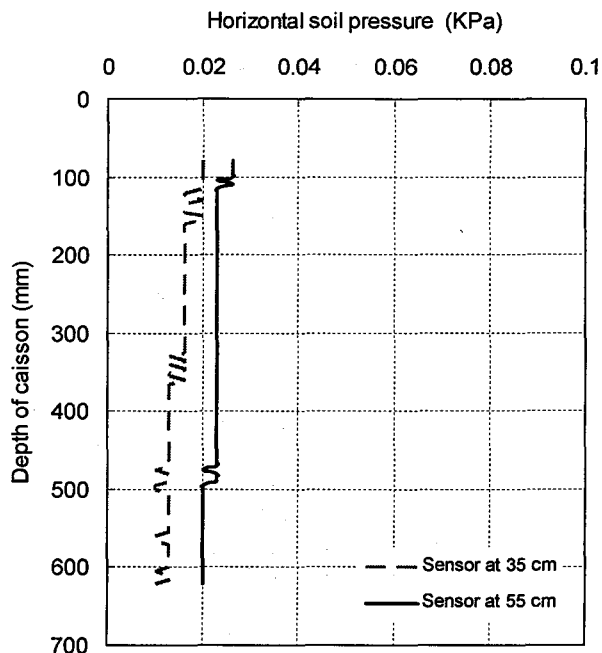
four different water contents (such as 2.5%, 3.3%, 4.6%, and 7.5%) were used in another four experiments under the same density and shear speed of the caisson model to study the effect of water content of soil on friction. The shear speed of the caisson model was also considered as variable due to its influence to caisson behavior under axial loading. Three different shearing speeds of 2, 10, and 30 mm/min were used in the next three experiments under same density and water content. Fig.7 shows friction stress against displacement of caisson model under four different densities while Fig.8 shows the distribution of horizontal earth pressure for the case of relative density of 93%.

The distribution of the friction stresses with penetration of the caisson model and horizontal stresses distribution are found to be similar to those of the normal caisson (Fig. 5 & 6). From Fig.5 and Fig.7, the friction stresses of SS caisson (space system caisson) are less than those values in normal caisson. This is expected that the contact area of the caisson model with space gravel is less than contact area of the caisson with soil due to larger diameter of gravel than soil particle.
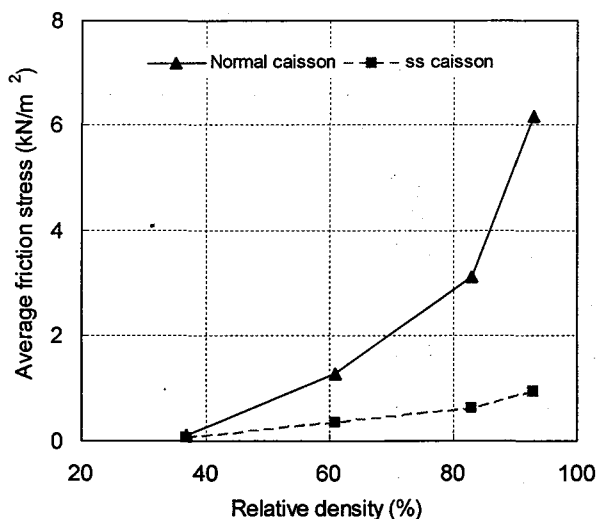
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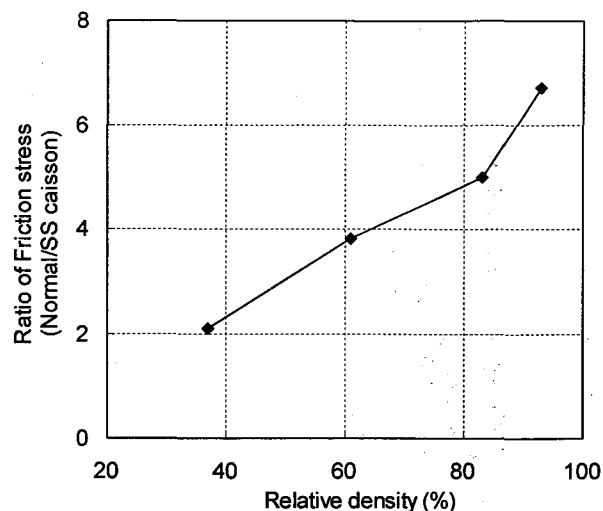**Fig. 9** Comparison of friction stress
for normal and SS caisson

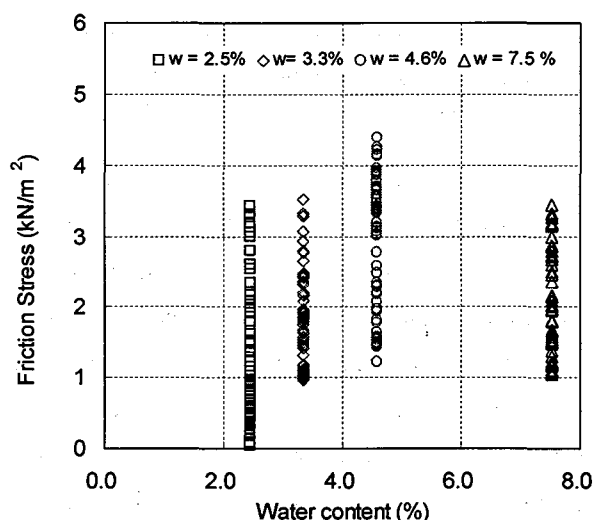**Fig. 10** Ratio of friction stress
of normal to SS caisson

Fig. 11 Friction stress distribution
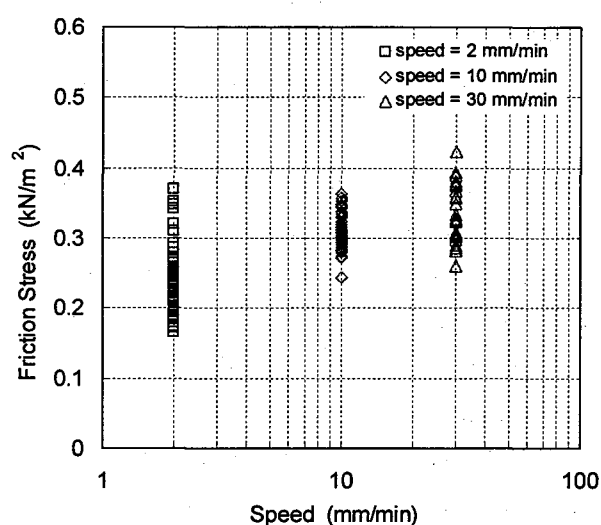with water content of soil

Fig. 12 Friction stress distribution
with penetration speed

Another contribution is moving of space gravels. While the caisson model is sinking, space gravels are also moving down with gravity. The moving of space gravel breaks the interaction between particle-to-particle and may cause less contact force between the caisson model and the particles (space gravels). This may result the less friction between the caisson wall surface and the gravel.

After the peak friction values, it approaches to constant (Fig.7). Although the soil densities were different, the friction stress values at deeper penetration were seen the same (Fig.7). It may be overcome the

density effect at deep penetration.

Fig.9 shows the comparison of average friction stresses of normal caisson with those values of SS caisson. And Fig.10 shows the ratio of friction stresses of normal caisson to SS caisson with respective densities. From these figures, it is clearly seen that friction stresses in SS caisson (space system caisson) are much less than those value in normal caisson at all densities of the soil. By these results, it is confirmed that the SS caisson method can reduce the surface friction of the caisson.

Fig.11 shows the friction stresses with different

water contents. Although water contents were different, the friction stresses were seen the same value. The water content of soil sample does not affect the friction between caisson and space gravel. The space gravels stand as a one vertical layer between the caisson wall and the soil surface. The same result was found with different penetration speeds. Fig.12 shows the friction value at different penetration speeds. Friction stresses were found the same at different caisson penetration speeds. It may be compared with simple shear test on granular material with fully drained. This may expected that effect of shear speed diminished.

5. CONCLUSION

The space system caisson (SS caisson) method is the construction method that reduces the friction force between caisson wall surface and soil by using space gravel. Its major feature is the sinking facility with no external loading. A newly experimental setup was developed and laboratory investigation was done. The results presented in this study are only applicable for direct axial compression. Friction increases with density, but water content and penetration speed give almost no effect to friction. By using the gravel between caisson and soil, it is found that friction becomes relatively less. Therefore, the effectiveness of friction force reduction by the SS caisson foundation was confirmed.

References:

1)Potyondy, J.G. (1961). "Skin friction between various soils and construction materials." *Geotechnique,* (11), 4, 339-353.

2)Acar, Y. B., Durgunoglu, H. T., and Tumay, M. T (1982). "Interface properties of sand." *J. Geotech. Engrg. Div.,* ASCE, 108(4), 648-654.

3)Vesic, A. S. (1970). "Tests on instrumented piles, Ogeechee River site." *J. Soil Mech. And Found. Engrg. Div.,* ASCE, 96(2), 561-584.

4)Lehane, B. M., Jardine, R. J., Bond, A. J., and Frank, R. (1993). "Mechanisms of shaft friction from instrumented pile tests." *J. Geotech. Engrg. Div.,* ASCE, 119(1), 19-35.

5)Terzaghi, K. and Peck, R. B (1996). "Soil Mechanics in Engineering Practice, 3rd Edition, Wiley, New York.