SKIRT SUCTION FOUNDATION
- APPLICATION TO STRAIT CROSSINGS -

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Abstract

Since early 1970's skirt suction foundations (skirted foundation / bucket foundation) have been used as support for large fixed substructures or anchors for floating structures in offshore hydrocarbon development projects. In recent years skirt suction foundations are recognized as one of the solutions in foundations applicable to bridge substructures installed in waters, because skirt foundations have a wide variety of functions such as control of settlement during service life, less impact to environments during operation at installation site.

This paper introduces general features of skirt suction foundations, and then discusses design practice of them for the application to bridge substructures, with reference to experiments in both laboratory and field.

1. Introduction

Since 1970 offshore structures have employed skirt suction foundations (so called skirted foundations or bucket foundations). Skirt, hollow cylindrical concrete or steel walls, is penetrated into seabed soil to transmit loads to deeper and stronger strata. So far approx. 30 concrete gravity based structures with skirt have been installed in waters 50-300m deep and numerous cylindrical suction anchors and piles with 5-10m diameters installed in waters 100-2,000m deep. The skirt suction foundations utilize a hydrostatic pressure at any stages from fabrication and installation (such as skirt penetration) to service. Therefore, they require some water depth at the installation site.

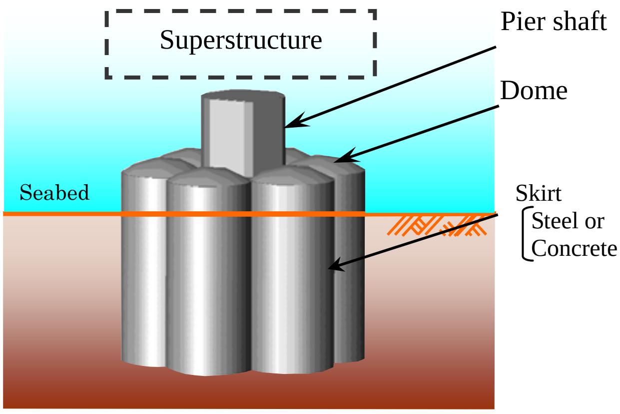

Fig.-1 Skirt Suction Foundation

Fig.-2 Troll platform installed '95

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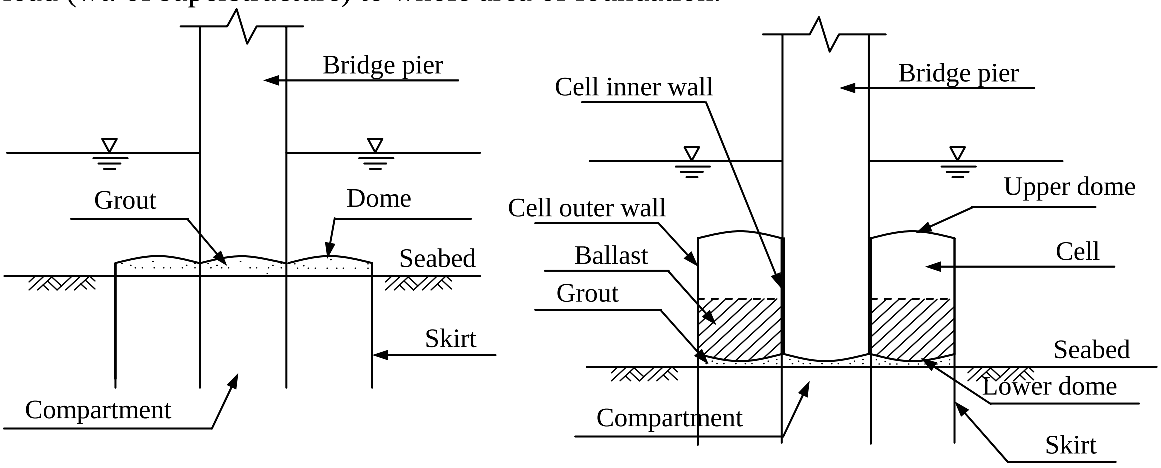
2. Structural configuration

The skirt suction foundations for bridge substructures consist of cylindrical concrete walls (skirts) projecting down the dome, as shown in **Fig.3**. The diameter of the cylinder is normally 12-15m and wall thickness is 0.4-0.5m. The space in a cylinder is called “compartment”.

In case of large foundation for such as long span bridges installed in deep water the substructures are provided with cells on top of the lower dome to transmit the applied load (wt. of superstructure) to whole area of foundation.



[Typical foundation] [Large foundation with cells]

Fig.3 Structural configuration of skirt suction foundations

3. Suction effect

“Suction” provides increase or decrease in hydrostatic pressure by pumping water from and to skirt compartments. The following beneficial effects are expected by suction.

(1) Reduction of penetration resistance

During skirt penetration, pumping water provides an under-pressure in compartments and sets up seepage flow that reduces tip resistance together with internal friction. In case of sand or gravel strata, large suction degrades skirt tip resistance to approximately zero.

(2) Additional penetration force

If the water in compartments is evacuated, the downward load is provided by suction. This effect is applicable to both clay and sand.

(3) Leveling of structure

By adjusting hydrostatic pressure in compartments during skirt penetration, it is possible to control the inclination of structure due to heterogeneous soil condition or slope at sea bed. In extreme case pumped water into skirt compartment can raise the structure by an increased hydrostatic pressure.

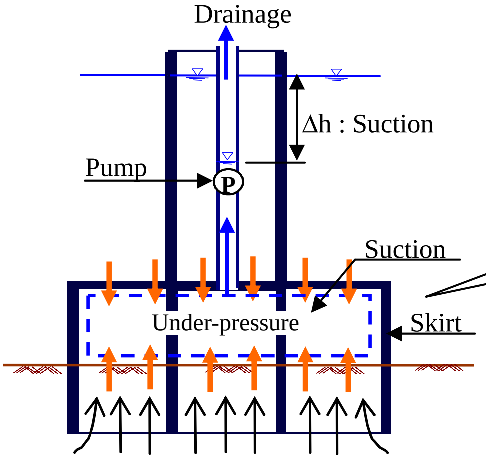


Fig.4 Seepage during suction installation

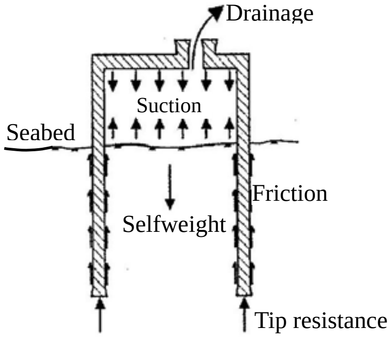
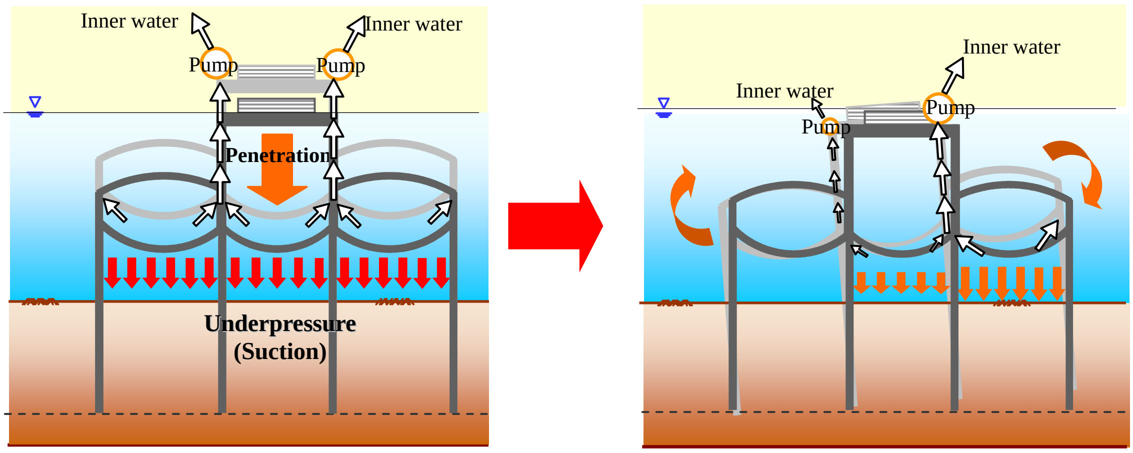


Fig.5 Force equilibrium during suction installation



[Penetration] [Leveling]

Fig.6 Penetration and leveling of foundation due to suction

The above effect is called "active suction". On the other hand "passive suction" effect is also expected. As reported in 20th BWS (2004), the existing research conducted at Public Works Research Institute (Japan) demonstrated that in foundations equipped with or without skirt passive suction is generated under the sealed baseplates in response to short term tension loads such as earthquake or storm. The findings of this research support significant tensile resistance of skirt suction foundations.

4. Application to bridge foundation

The skirt suction foundations for a bridge substructure expect the following effect over existing type of foundations.

(1) Reduction of settlement in service life (Preload effect)

During the skirt penetration and/or just after the installation of the foundation, large vertical load induced by suction is applied to substructure. If the suction load is greater than the imposed load (such as weight of superstructure) after installation, the settlement during service can be reduced by some extent.

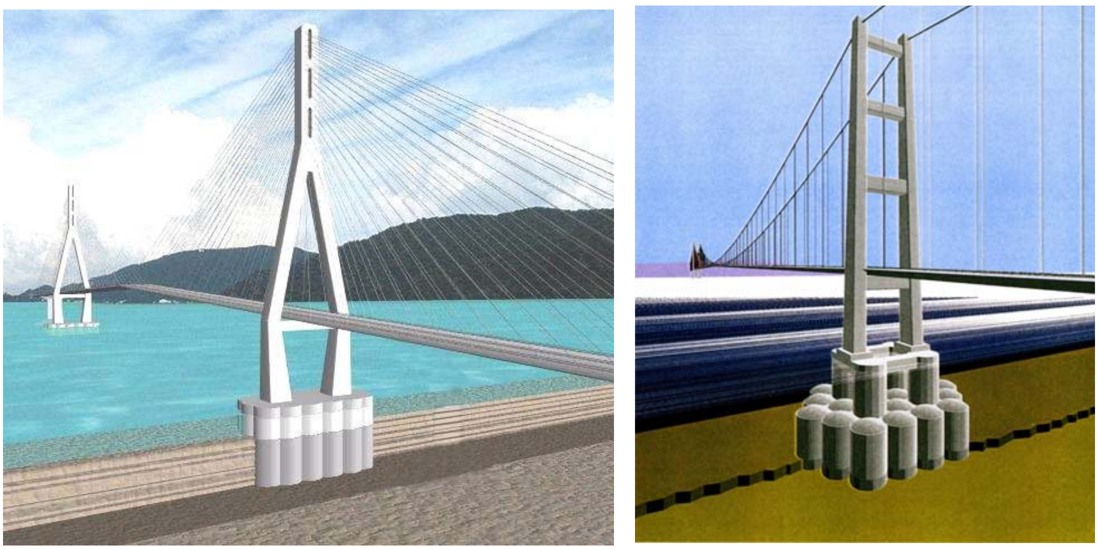
(2) Short construction period on site

The construction on site is only installation of foundations, because fabrication of skirts, domes and cells are conducted in dry docks and/or floating site (wet docks), if necessary, and foundations are towed to the site. Therefore considerably short occupancy of water at installation site is expected resulting in favorable effect on ship navigation and fishery.

(3) No soil improvement/dredging required

Foundation skirts have various function such as containing soft surface soils, compensating for seabed irregularities, reducing scour around foundation and transmitting load to bearing strata. Therefore no soil improvement and dredging is required in case of soft soil deposits and even in seabed slope. In addition, no noise and vibration is followed in the installation of skirt suction foundations. This means that skirt suction foundations are attractive to environments.

Water depth needs to be over 10m to utilize the above effects and skirt penetration is limited to cohesive soil, sand with a few gravels, or combination of those. Although the above limitation exists, possible bridge construction sites in Japan (Tokyo bay, Osaka bay and other shallow waters) have such a soil condition. Hence the skirt suction foundations are though to be applicable to substructure of the bridges in Japan.



［Center span : 500～600m］　　［Center span : 2,000～2,500m］

Fig.7 Application of skirt suction foundation to bridge substructure

5. Evaluation of performance as bridge foundation

It is necessary to satisfy various performances specified in "the Specifications for Bridges in Japan" to apply the skirt suction foundation to bridge substructures. In addition, the following observation and experiment have been conducted to evaluate the typical performance of skirt suction foundations for bridge substructures.

(1) Leveling of foundation at penetration
(2) Preload effect by suction (Reduction of settlement)
(3) Seismic behaviour of foundation

The first two performances are explained in this paper.

5-1 In-site monitoring for penetration and leveling of foundation

First evaluation concerns the control of leveling of foundation. The offshore concrete structure shown in Fig.8 with the skirt 18m diameters and 5.0-5.5 height was installed with suction. It is required to protect the jetty from impact of ship out of control. The soil feature has the surficial soft clay of 3.5m thickness and medium dense sand below it. Photo1 shows that the structure was dry-towed by the heavy lift barge and lowered at the installation site.

The penetration of skirt is quite important process for this type of foundation. The skirt penetration should include the steep slope of the bearing strata. In order to overcome these obstacles, the penetration operation was divided into two process - skirt penetration and control of leveling. The former penetrated the skirt with suction until near the target depth and the lift barge assisted the operation throughout. The latter, without assistance from the lift barge, took the role of leveling of inclination and deeper penetration.

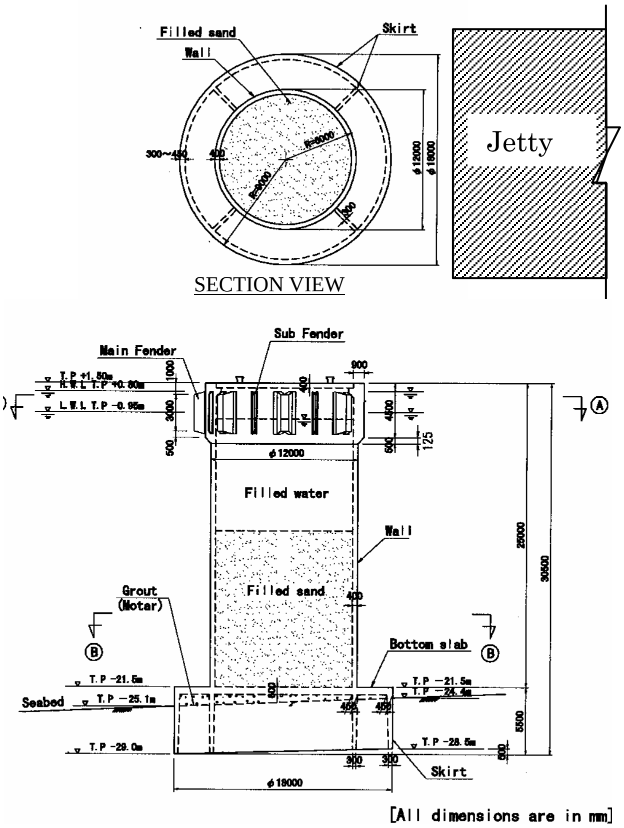


Fig.8 Dimensions of structure

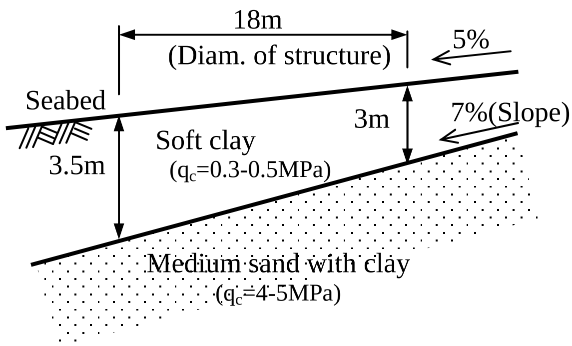


Fig.9 Soil strata

Photo1 View of protection just before skirt penetration

(1)Skirt penetration

After the accurate positioning the lift barge slowly lowered the structure until the skirt tip contact with subsoil, the touch-down. The very small penetration resistance was observed during the penetration in the surficial soft clay. However, the penetration resistance suddenly increased just after the penetration into the sand layer. The relation of penetration load with skirt tip depth is illustrated in **Fig.10**. The slope of the sand layer resulted in the inclination of 1.6 degree of the structure.

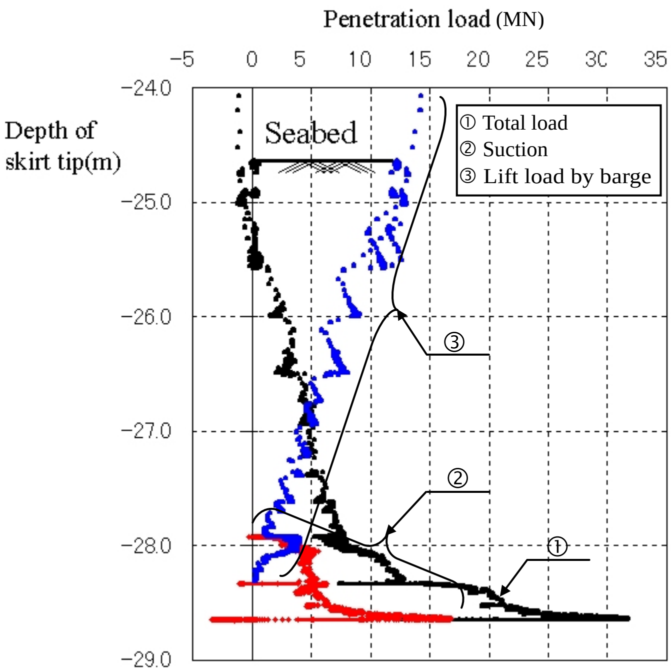


Fig.10 Penetration load vs skirt tip depth

(2) Control of inclination

By providing different suction for each skirt compartment, the inclination of the protection was well controlled. **Fig.11** shows that the suction of 10-15m water head (under-pressure) was applied to compartments②-⑤ and the reverse suction (over-pressure) of 15m head was given to compartment①. The inclination was adjusted within two hours; from 9am to 11am. The final installation was 0.3degree. No piping was observed, although these suction pressures were much higher than those for boiling obtained from a conventional formula including soil weight and friction with wall.

Due to the impervious surficial clay the reduction in the vertical effective stress of the sand was negligible, which resulted in no reduction in tip penetration resistance in the sand.

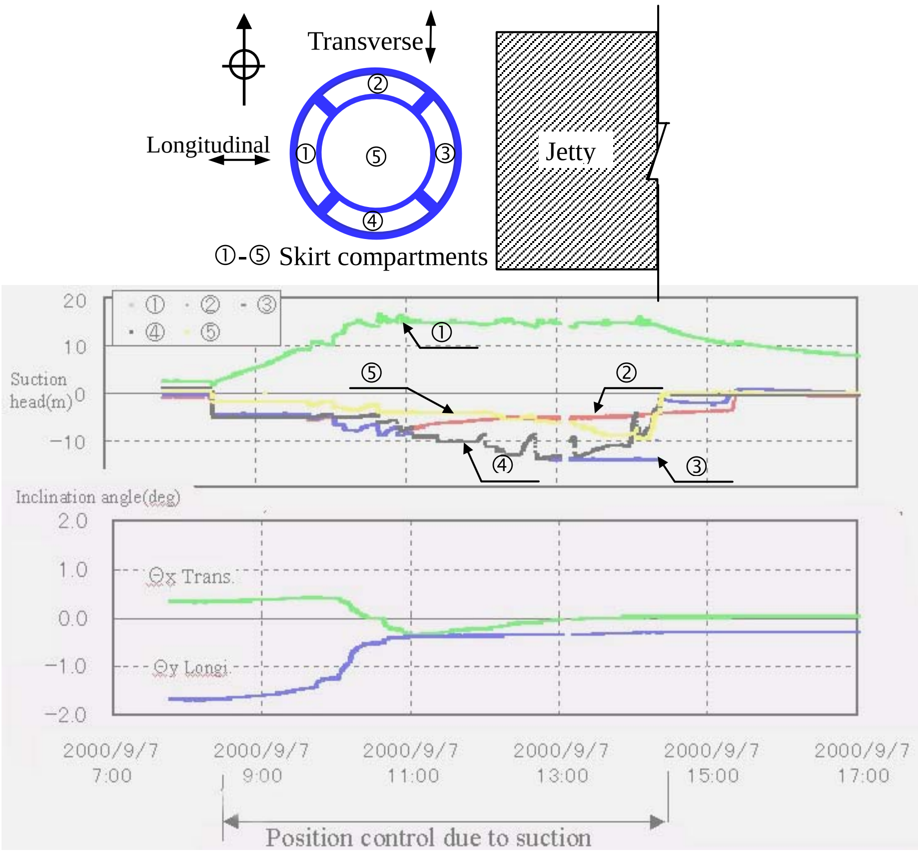


Fig.11 Control of inclination due to suction

5-2 Experimental evaluation of preload effect due to suction

Second evaluation relates to the preload effect, whose concept is illustrated in Fig.12. The penetration of skirt requires selfweight, ballast as well as suction (under pressure) of skirt compartments. If the load induced by suction (called “suction load”) is greater than the imposed load during the service, the settlement due to them could be considerably small as shown in **Fig.12**. Therefore, the suction is applied during installation and removed after it and the suction load is termed as “preload”. However, the effect of preload due to suction is not well understood, because the suction is not externally applied load but internal action and the effective stress in the surficial soil is temporarily reduced. The experiment using a centrifuge apparatus was executed to verify the effects of preload for skirt suction foundation. Details of the experiment are explained below.

(1) Purpose

The experimental approach investigates the difference in the preload effect between internal load due to suction and external load due to jacking.

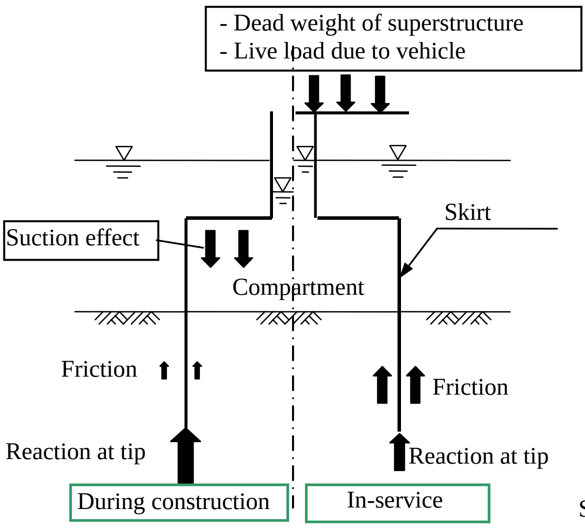


Fig. 12 Concept of "Preload" due to suction

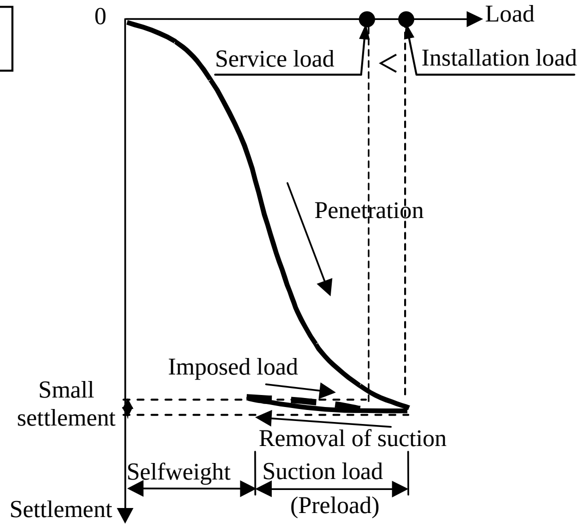
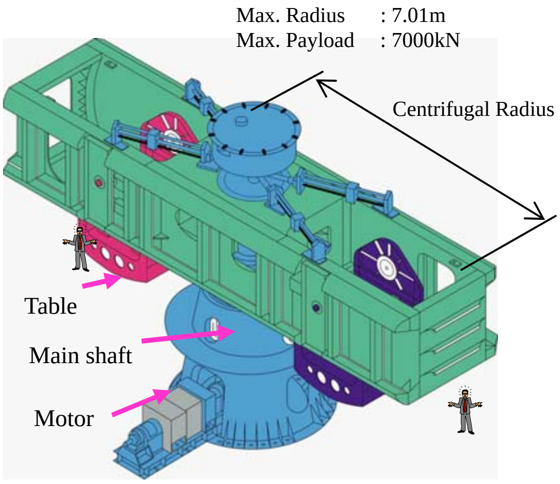


Fig. 13 Schematic description of preload effect

(2) Apparatus

The centrifuge scale model has been employed here. The centrifuge apparatus shown in **Fig.14** has the boom radius of 7.01m, table space of 2.2 x 2.2m and maximum acceleration of 120g.

The apparatus of the experiment on the table is shown in **Fig.15**. The filled sand in the container of 800mm diameter is fully saturated and has 550mm depth. The water depth is 250mm. The test specimen made of plastic has single skirt compartment with diameter of 150mm and wall thickness of 8mm and it was penetrated into the depth of 200mm under an atmospheric pressure. Then the acceleration was applied up to 30g and the further penetration was conducted with the rate of 1.3mm/min. The water pressure in the skirt compartment was controlled by the adjustment of water level of the tank through monitoring the pore pressure gauge installed in both the tank and the skirt compartment.



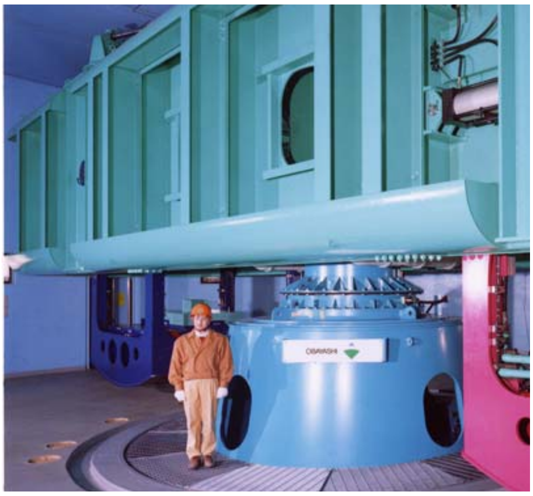


Fig. 14 Centrifuge facility for experiment

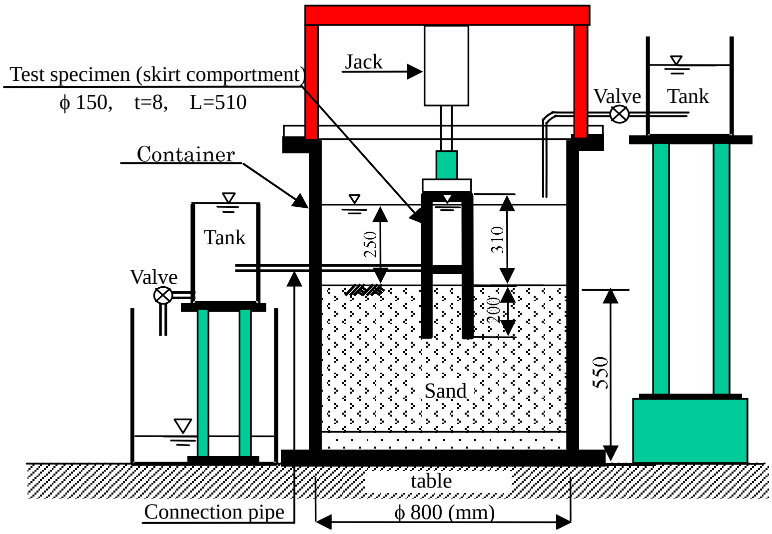


Fig.15 Apparatus and scale model of experiment on table

(3) Results and discussion

The test cases are shown in **Fig.16**. Case-2 expects the reduction in penetration resistance as well as the suction load.

Case-1 Penetration by jacking

Case-2 Penetration by suction together with jacking

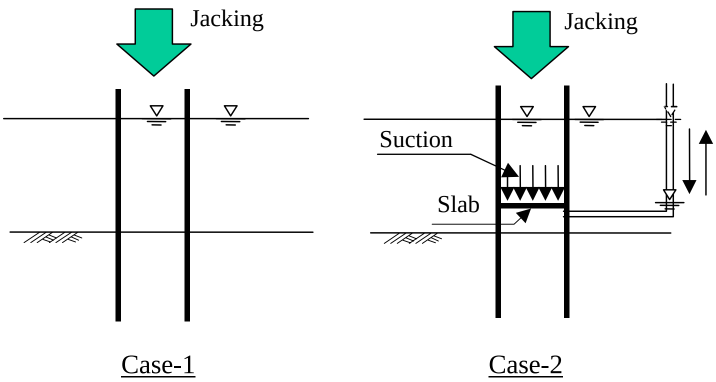


Fig.16 Test cases for preload effect

The load-settlement curve of Case-1 shown in **Fig.17** demonstrates that the reload after unload shows almost no settlement at the penetration depth both of 6.3m and 7.3m. It is found that the preload effect due to jacking was clearly observed. **Fig.18** shows the load-settlement curve in Case-2 where the penetration load up to the depth of 6.3m was applied by the jacking, then the suction was included until 6.8m depth, and the further penetration load was induced by jacking after removal of suction. The unloading and reloading was conducted at the skirt tip depth of 6.8m.

When the suction was applied during the penetration, **Fig.18** shows that smaller imposed load (5KN) in Case-2 than that in Case-1 is enough to penetrate the skirt until the depth of 6.8m due to the upward water flows induced by suction load of 0.7KN.

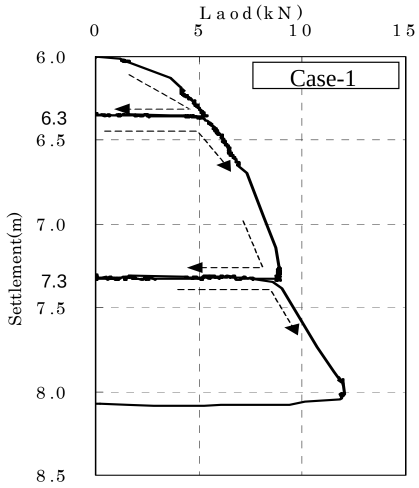


Fig.17 Load-settlement curve of jack preloading

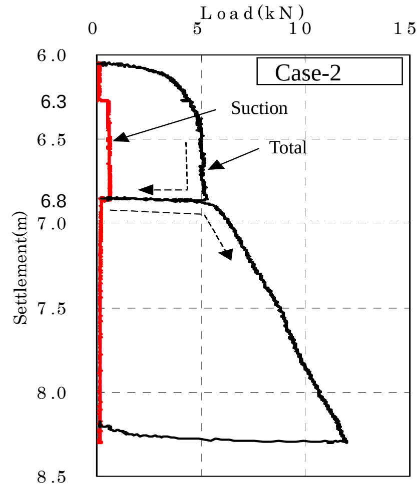


Fig.18 Load-settlement curve of suction preloading

After the removal of suction load at the depth of 6.8m the reloading was applied by jacking and the load – settlement curve shows that the settlement by the reloading until the preload (5kN) was nil just same as Case-1 due to the preload effect.

However, the penetration resistance at the same depth in Case-1 and –2 has a little difference because it might depend upon the load hysteresis during penetration.

An additional experiment has been conducted to verify the preload effect due to suction. This second experiment Case-3 employed the same apparatus as shown in **Fig.15** but different scale model illustrated in **Photo2**, whose dimensions are as follows.

Photo2 Additional scale model for experiment for preload in Case-3

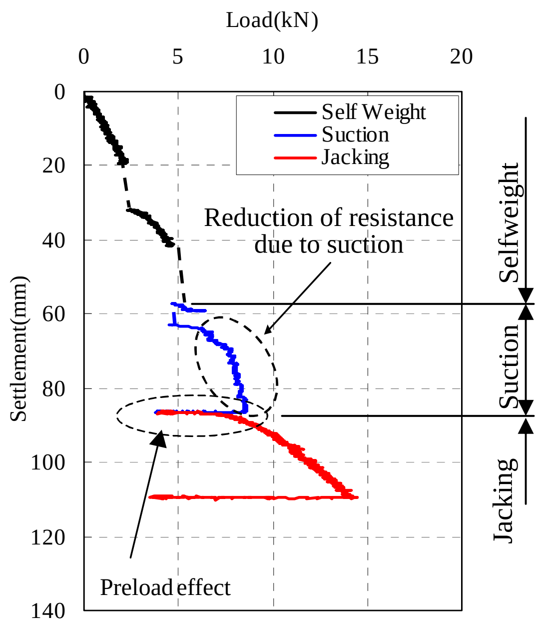


Fig.19 Load-settlement curve of Case-3

Diameter of outer compartment	ϕ_0	=370mm
Diameter of inner compartment	ϕ_I	=150mm
Height	h	=250mm
Wall thickness of compartment	t	=4mm

The test specimen was penetrated by suction and then reloaded by jacking as before. The result in **Fig.19** illustrates the load-settlement curve of both penetration and reloading. Until the depth of 60mm the applied penetration load was only the selfweight, and then the suction was imposed to reduce the penetration resistance up to the depth of 85mm. After the removal of suction the reload was imposed by jacking. The preload effect was clearly observed because of no significant settlement during reloading. Further the jacking beyond the hysteresis load (8kN) highly increased the penetration resistance which approached the load – settlement curve due to external loads.

Conclusions

The following performance of skirt suction foundations as a bridge substructure was observed by experiments in the field and laboratory.

(1)The offshore structure with skirt foundation was successfully installed. The position of a structure was well controlled by suction during and just after the skirt penetration. The installation accuracy was 0.5% of inclination, without soil improvement or dredging.

(2)Preload effect by suction was well observed, because the reloading by jacking up to the preload induced by suction showed no significant settlement of the foundation.

(3)Not only the above performances but also the tensile resistance due to seismic loading clearly shows high applicability of skirt suction foundation to bridge substructure installed in waters.

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