Present situations and problems in design and construction of caisson foundations in Japan

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Summary: The caisson foundation is a one of the typical foundation type in Japan, and mainly used for larger-scale bridge foundation because it's big bearing capacity. However, recently, the share of caisson foundation has been decreased. The caisson of this situation can be considered that the difficulties of construction.
Therefore, various technical development has been carried out and some of them are used in-site, for example, the unmanned excavation system aided by remote-controlled excavation machines and so on.
The seismic design of bridge foundation including caisson foundation in Japan revised several times based on the lesson from large earthquake, for example, Niigata Earthquake (1969), Hyougoken-nanbu Earthquake (1995). Present seismic design method has been systematized with the analysis of a seismic response.
This paper shows the present situations and problems in design and construction of caisson foundation under such circumstance in Japan.

1. Introduction

This report describes the pneumatic caisson method and the open caisson method as a deep foundation. The former method is performed using a caisson including a worker chamber made up of external walls and a ceiling slab at its bottom, forming to be open to the ground that is excavated beneath it. As compressed air is pumped into this working chamber to keep it free from water, and workers and machines can excavate and remove soil from beneath it, the caisson body is lowered until the excavation has been completed down to the design bearing stratum.

Its features are:
[1] Because the excavation work can be done in an atmosphere identical to that at the ground surface, it is able to excavate all kinds of soil from clay to rock.
[2] This means that it is possible to count on the excavation work being completed satisfactorily and to execute the work according to the construction project plan.

Shortcomings are:
[1] It is difficult to construct extremely deep foundations.
[2] The excavation facility is large scale.

The latter method is a performed by lowering a caisson body to the design bearing stratum as clam shell buckets or grab buckets are used to excavate and remove the soil inside the caisson.

Its features are:
[1] It is performed by repeating a simple execution procedure.
[2] Depending on the soil quality, it can be used to construct extremely deep foundations.

Shortcomings are:
[1] Excavation under cutting edge cannot be performed.
[2] It is difficult to deal with settlement or inclination of the caisson body.

Table.1, which presents the kinds of foundations selected for Japanese highway bridges (span length of 20 m or more) up to 1995, reveals that the number of caisson foundations constructed has declined in recent years.

	1966	1975	1985	1995
Spread Foundation	125	1.263	1.526	1.869
Pile Foundation	207	1.383	1.996	2.942
Caisson Foundation	117	170	145	81
Steel Pipe Sheet Pipe Foundation	-	-	30	59
Cast-in-site Diaphragm Wall	-	-	-	6
Others	-	-	-	38
Totals	449	2.816	3.697	4.995

Table.1 Changing Highway Brige Foundation Construction Methods in Japan

There are two reasons for this tendency.
[1] The fact that pile foundation has high applicability for various kind of soil and it is now possible to construct large diameter piles.
[2] The development of new forms of foundations stood for steel pipe sheet pile foundations and diaphragm walls foundation.

Fig. 1 shows that many of those caisson foundations, which support long span bridges, have been constructed at locations with very deep water. The reason of this situation is that they are appropriate for deep foundations thanks to the benefits cited above and the large bearing capacity of a caisson foundation.

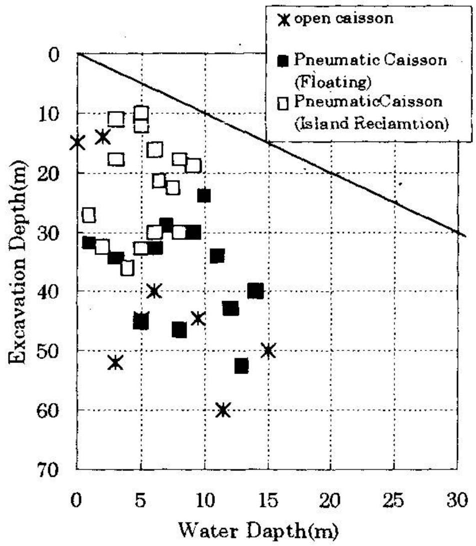

Figure.1 Underwater caisson Foundation Executions in Japan

2. History of the Development of Caisson Execution Technology in Japan

2-1. Pneumatic Caisson

The first pneumatic caisson as highway bridge foundation constructed in Japan was the foundation of the Eitai Bridge (Tokyo) in 1925. Afterwards this method was frequently used to construct deep foundations until the late 1960s. It is necessary to limit the period that workers spend in the working chamber in order to protect them from decompression illness and other dangers of working in high pressure environments, therefore the higher the pressure in the working chamber, the shorter the working time that excavation can be performed. As a result, it was necessary to replace manual excavation methods with more efficient mechanized excavation methods.
In the 1960s, tracked bulldozer-shovels powered by electric motors were developed. But because drivability of this machines were very bad at the excavation of soft clay, new systems with the excavation shovels moved along rails installed on the ceiling of the working chamber were developed during the 1970s. Because these new systems were operated by workers seated on the machinery itself, they were still subject to the effects of the highly compressed air. In 1989, a remote operating machine was developed. Operator can drive this machine from operating rooms located at ground level and free from the high pressure atmosphere in the working chamber.

2-2. Open Caisson

The first open caisson as highway bridge foundation must be the bridge that was completed in 1887. Afterwards many reinforced concrete caissons were constructed. The excavation was done primarily using the clam shell bucket method, and as the assistant method of caisson settlement, pressurized water or compressed air were injected towards the ground from the external wall. Then in the 1970s, a method of applying a special friction reduction sheet to the external wall was developed, and in the late 1980s, a press-in method employing ground anchors and center hole jacks was developed. These innovations are still in use.

3. Recent Trends in Caisson Execution Technology

3-1. Pneumatic Caisson

The remote operation method is often used when the pressure in the working chamber exceeds 0.294 MPa, and it had been used a total of 46 cases according to a May 1997 survey. Even when this method is employed, workers have to work in the high-pressure area to inspect and repair the machinery, lighting fixtures, and so on. When workers breathe air at a pressure in excess of 0.392 MPa, they suffer the symptoms of nitrogen narcosis. To prevent this from happening, a respiration system that supplies a helium, nitrogen, and oxygen mixture with low nitrogen content was introduced in 1995 and has now been employed at five caisson foundation construction sites. The method is now applied where work is performed in high-pressure conditions experienced at a depth of 70 meters under the surface of the water.

Category		Location	Bridge Name	Foundation Specifications (m)		Super-structure	Center Span Etc. (m)	Water Depth (m)	Vertical Ground reaction per unit area at the bottom of foundation (kN/m^2)	Foundation Ground
				Plane Dimensions	Embedding Depth from Sea Bed or Ground Surface					
Underwater Foundation	Floating caisson	Tokyo Bay / harbor	Rainbow Bridge	70.0×45.0	34.5	Suspension bridge	570	12.0	1290～450	Alluvial clay to hard pan
	Double wall cofferdam	Osaka Bay / harbor	Kodai Bridge	40.0×40.0	30.5	Gelbar truss bridge	510	4.0	420.0	Alluvial clay to diluvial gravel to rock
	Island reclamation	Hokkaido / harbor	Hakucho Ohashi Bridge	46.0×33.0	21.0	suspension bridge	720	7.0	–	Alluvial clay to diluvial gravel
	Floating caisson	Osaka Bay / harbor	Higashi Kobe Bridge	35.0×32.0	27.5	steel cable-stayed bridge	485	9.0	656～453	Alluvial clay to diluvial gravel
	Floating caisson	Ise Bay / harbor	Meiko Chuo Bridge	34.0×30.0	35.0	steel cable-stayed bridge	590	14.0	910.0	Alluvial clay to diluvial gravel to rock
	Floating caisson	Ise Bay / harbor	Meiko Nishi Bridge	40.0×25.0	28.0	steel cable-stayed bridge	405	12.0	–	Alluvial clay to diluvial gravel
	Floating caisson	Korea / Inchon River	Eiso Bridge	47.0×18.0	30.85	Suspension bridge	300	10.0	–	–
	Constructed on site	Ise Bay / river mouth	Inde River Bridge	26.0×10.0	40.0	Steel box girber bridge	97.5	2.5	–	–
On-land Foundation		Tokyo Bay / harbor	Rainbow Bridge	70.0×45.0	39.0	Suspension bridge	570	–	1098～341	Alluvial clay to hard pan
		Kan-etsu Expressway / mountains	Nagai River Bridge	47.6×18.0	26.0	PC box girber bridge	123	–	–	Gravel
		Tomei reconstruction / mountains	Tomei Ashigara Bridge	ø18.0	22.0	PC cable-stayed bridge	185	–	–	To rock

Table. 2 Large scale Pneumatic caisson Foundations

The following unresolved challenges remain.
[1] Shortening the caisson body construction work process to balance it with the excavation process
[2] Gaining the ability to work at deeper levels by researching saturation methods for mixed gas respiration and the joint use of other construction method such as the soil freezing methods.

3-2. Open Caisson

The Super Open Caisson System (SOCS method), an automatic open caisson technology, has been developed as a joint public - private sector research project at the Public Works Research Institute of the Ministry of Construction.

This new technology provides the following benefits.
[1] It includes newly developed excavation machinery that can reliably excavate the ground under the cutting edge of the caisson down to great depths. It permits automatic operation of the excavation machinery in harmony with soil lifting equipment.

[2] It permits the excavation and caisson attitude data to be linked to perform automatic press-in settlement control.
[3] To rationalize the execution of the caisson body construction, prefabricated caisson bodies were developed.

This new system has been used to perform excavations down to a maximum depth of 53.5 m. All that remains to be done is to loser its cost and expand the range of soil types it can be used to excavate.

Category		Location	Bridge Name	Foundation Specifications (m)		Super-structure	Center Span Etc. (m)	Water Depth (m)	Foundation Ground
				Plane Dimensions	Embedding Depth from Sea Bad or Ground Surface				
Underwater Foundation	Crane lowered	Hiroshima Bay / harbor	Umeda Bridge	ϕ16.0	50.0	Steel box girder bridge	250	10～15	Alluvial clay to diluvial gravel
	caisson	Hiroshima Bay / harbor	Hiroshima Bridge	ϕ10.0	45.0	Steel box girder bridge	150	15.0	Alluvial clay to diluvial gravel
	On-land execution	Ise Bay / river	Kiso-sankyo Bridge	ϕ11.0	52.0	Steel Truss	—	—	Sand/clay to gravel
	(Island reclamation method)	Ariakeumi / river	Nitta Bridge	ϕ9.0	40.5	Stiffened arch bridge	—	9.0	Alluvial clay to gravel
On-land Foundation		Kanetsu Expressway / mountains	Nagai River Bridge	43.5×16.5	10.0	PC box girder bridge	123	—	To gravel

Table. 3 Large Scale Open caisson Foundations

4. Caisson Foundation Design Methods: Present Status and Future Challenges

4-1. Present Design Methods

4-1-1. General Items
Design standards for highway bridge have been issued as a notification of the Ministry of Construction under the title, "Technical Standards for Bridges and Highway Viaducts." Regarding standards for caisson foundations, since "Design of Caisson Foundations" was issued in 1970, it has been steadily revised and enacted in 1980 under the title, "Specifications for Highway Bridges, Part IV: Substructure " as integrated guidelines for substructure. The seismic design method for foundations stipulated in these standards were the seismic coefficient method. By the lesson from the Hyogo-ken Nanbu Earthquake of January 1995, seismic design was radically revised; the seismic coefficient method was supplemented by verification based on the ductility design method.

4-1-2. Design Model of a Caisson Foundation
a) Rigidity of the caisson body
A caisson body is modeled as a single column, and is in principle, an elastic body. But the ductility design method accounts for a decline in rigidity caused by cracking or the yield of rebar.
b) Ground Resistance
The ground resistance is an elasto-plastic spring model as shown in Figure. 2 to account for the horizontal resistance, the vertical shear resistance on the front, the horizontal shear resistance on the side, the vertical resistance, and the shear resistance on the bottom. But accounting for the execution procedure, the self-weight was assumed to act only on the bottom of the foundation. The maximum value of the horizontal resistance is treated as Coulomb's passive resistance earth pressure, and the ductility design method accounted for three dimensional expansion of the passive resistance range.

4-1-3. Caisson Foundation Stability Calculations
a) Normal conditions, earthquake conditions in case of seismic coefficient method and storm

conditions
On the premise that the caisson body and the ground at the bottom surface are in the elastic range, it is verified that the horizontal displacement, vertical and horizontal ground resistance at the bottom, and the member stress are all below the allowable values.
b) Seismic design based on the ductility design method
This method verifies that the horizontal capacity of the foundation is equal to or greater than the ultimate horizontal capacity of the bridge pier body, or in other words that when a load that corresponds to the ultimate horizontal capacity of a bridge pier body acts on foundation, the overall behavior of the foundation does not reach the yield of the foundation. When the term "yield of the foundation" is defined as the state where horizontal displacement at the inertial force action point of the superstructure begins to rise rapidly as the horizontal load rises.

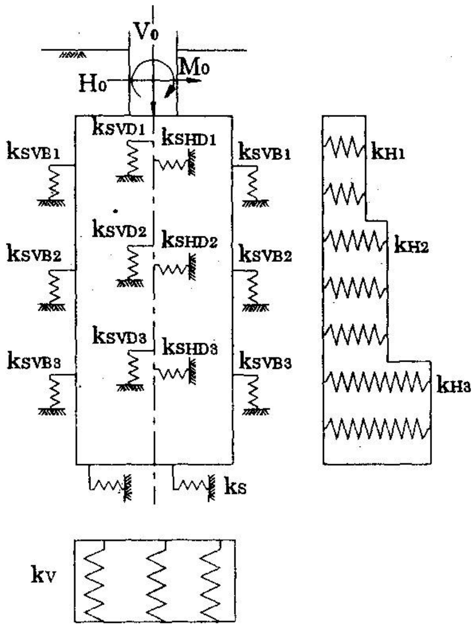

Figure. 2 Ground Resistance

4-2. Bearing Capacity Design: Present Status and Challenges
Because one feature of the caisson construction method is that it is possible to confidently embed a body with high rigidity on the bearing stratum in order to obtain high bearing capacity, this section describes the evaluation of bearing capacity.

4-2-1. Present status of bearing capacity design
The ultimate bearing capacity of the ground at the bottom of a caisson foundation for a highway bridge is generally found based on the results of soil tests and soil explorations and using a formula (1) that is similar to the Terzaghi bearing capacity formula premised on the general shear failure of the ground. Because a deep foundation such as a caisson foundation resists the horizontal load or overturning moment aided by the ground at its front surface, only a little of the load is borne by the ground at its bottom surface. So equation (1) ignores the eccentricity and inclination of the load.

$$qd = \alpha \cdot c \cdot N_c + 0.5\,\beta \cdot B \cdot \gamma \cdot N_\gamma + q \cdot N_q \quad \text{-------------------(1)}$$

Where:

qd	=	ultimate bearing capacity (kN/m^2)
α , β	=	shape factors
N_c, N_γ , N_q	=	bearing capacity factors
c	=	cohesion of the ground at the bottom surface (kN/m^2)
B	=	width of foundation (m)
γ	=	unit weight of the bottom surface ground (kN/m^3)
q	=	weight of the soil above the foundation bottom (kN/m^2)

When a caisson foundation is deeply embedded, the ultimate bearing capacity calculated using formula (1) is extremely large. But the quantity of settlement during this ultimate bearing capacity is not clearly known. In the case of large foundation dimensions where it is impossible to ignore the quantity of settlement for the stability calculations, a designing maximum value of the allowable vertical bearing capacity is established considering this fact in order to perform the stability calculations for normal condition or the seismic coefficient method referred to above. This maximum value, which is shown in Figure. 3, is obtained by modifying the results of plate loading testing of the pneumatic caisson added an engineering judgment.
To use the ductility design method, an elasto-plastic spring model with the ultimate bearing capacity of the bottom surface ground obtained from formula (1) as the maximum value is established.

4-2-2. Challenges

The plate-loading test performed inside the working chamber of a pneumatic caisson during construction has, in some cases, obtained an ultimate bearing capacity of about 10,000 kN/m². But the experimental maximum value of the bearing capacity shown in Figure. 3 is set very low to obtain a value on the safe side in engineering terms. It is, therefore, necessary to establish more precise formulae to estimate bearing capacity and quantity of settlement in order to perform more economical foundation design work.

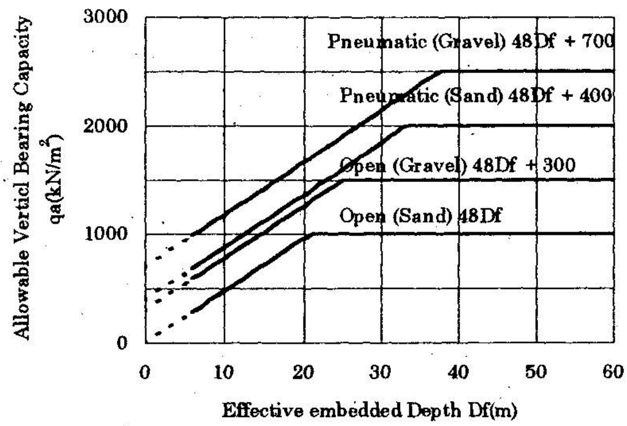

Figure. 3 Maximum Value (Normal Conditions) of the Allowed Vertical Bearing Capacity of the Ground at the Bottom Surface of a Caisson Foundation

It has been pointed out that there are discrepancies between the measured and theoretical equation (1) values with the static formula, even in the case of a shallow foundation: the existence of the scale effect of the bearing capacity factor for example. The scale effect of the bearing capacity factor is gradually being clarified thanks to the performance in recent years of more precise gravity field or centrifuge model tests, and by performing large bearing capacity tests of spread foundations in natural solid ground[1].

And to expand and apply the shallow foundation bearing capacity theory to deep foundations, various problems including that of the disparity of the failure mechanisms of the two kinds of foundation must be overcome. For example, while the embedment effect increases the bearing capacity, it also makes the stress-dependency of the shear resistance angle of earth ϕ used to calculate the bearing capacity factor becomes remarkable. It is also not clear if the shape factor of a shallow foundation that is set primarily based on test results and experience-based judgments can be applied to a deep foundation without modification. And even the deep foundation theory proposed by Meyerhof and Vesic is still plagued by many unresolved problems that are currently under research. These include the problem of the discrepancies on the theoretical model caused by the difference in the size of piles and caissons, the determination of the ground constants for design use, and so on. Remarkable progress in computation technology and ground exploration technology seen in recent years are expected to contribute to the final establishment of a bearing capacity estimation formula for caisson foundations based on the perfect plasticity theory and elasto-plastic theory.

On the other side, there is lively research activity underway to develop methods of estimating bearing capacity using FEM analysis methods that precisely model the strength deformation properties of ground based on the results of extremely detailed soil tests. In order to obtain data needed to verify the effectiveness of this method, eccentric loading test of spread foundations incorporating pneumatic caissons are being conducted on dense fine sand ground during foundation construction [2]; Through these tests and analysis that is expected to provide a practical working bearing capacity estimation method that also accounts for settlement so that it can be applied to deep foundations as well as shallow foundations.

Reference:

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2) Oyake, T., Ohuchi, M., Kimura, Y., Nakano, M. and Tatsuoka, F.: Field model bearing capacity tests on a Pleistocene sand deposit, Foundation Failures, May 1997, Singapore, pp 1 - 12.