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New Types of Undersea Foundations for Next Generation Projects

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Summary

In Japan, various types of undersea foundations have been developed for use in the construction of the Honshu-Shikoku Bridge and other bridges across straits. But the next generation projects now at the planning stage will require the construction of deep water foundations under conditions more severe than the Honshu-Shikoku Bridge. If these conventional foundations are used under such conditions, their size will be huge, and their construction will be difficult or even impossible. The authors have proposed two new types of undersea foundation: twin tower foundation and hollow rigid foundation. They have also analyzed the settlement of foundations using FEM based on the ground conditions at proposed project. The results have confirmed the stability of foundations with dimensions far smaller than those of conventional foundations. They have also pointed out problems with the construction.

1. Undersea foundations constructed in Japan

Figure 1. shows past executions of deep water foundations in Japan. It presents the relationship between the water depth and the depth of the bottom surface of the foundation for typical types of foundation. The following are the characteristics of each foundation type. The laying-down caisson type is constructed where the bearing layer is close to the sea bottom. Figure 2 shows how the depth of executions of this foundation type has increased. The main tower foundation of the Akashi-Kaikyo Bridge is the largest of this kind; constructed in water that is 50m in water depth, with its bottom surface 60m below the surface of the sea, and consisting of 354,000m^3 of concrete. Caisson foundations are constructed in water that is no more than 15m water depth, but the maximum depth of the foundation bottom surface is 60m. When diaphragm wall foundations are constructed under the water's surface, it is necessary to provide a filled cofferdam. The deepest foundation of this kind that has been constructed is 55m in depth, but it will be able to construct to a depth of more than 100m because it is excavated with machinery. Multi-column foundations are executed at water depth ranging from 5m to 20m. The maximum pile embedment depth of this type is 70m, using concrete piles with a diameter of 10m.

The above facts indicate that the principal factors that determine the type of undersea foundation are the depth of water, the depth from the sea bottom to the bearing layer, and the scale of the load. Where the bearing layer is shallow, a laying-down caisson is best regardless of the depth of water. Where the bearing layer is deep, consideration is given to the use of a column type foundation such as caisson or diaphragm wall foundation and to a pile type foundation such as a multi-column foundation or bell type foundation. Because the former types provide high rigidity, they are useful where the load will be large, while the latter are best where the water is deep.

2. Proposal of new type foundation

Figure 3 shows the locations and outlines of the ocean strait where highway bridge projects now at the planning stage. The routes, bridge types, and foundation locations for each projects are all under study at this time. The following are the hypothetical foundation conditions. The water depth at the main tower foundation ranges from 20m to 70m. The bearing layer of the ground is softer than that under the Honshu-Shikoku Bridge.

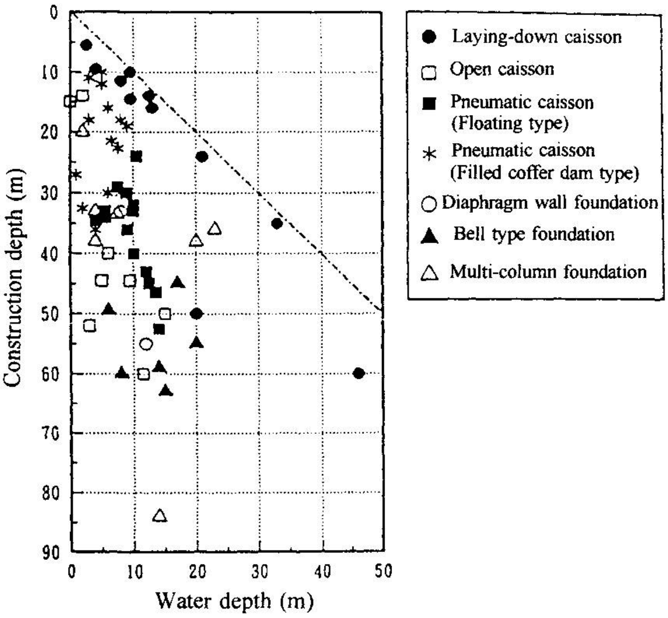


Fig. 1 Completed deep water foundation executions

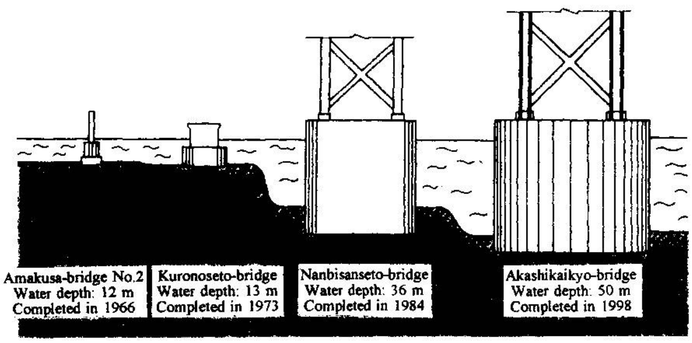
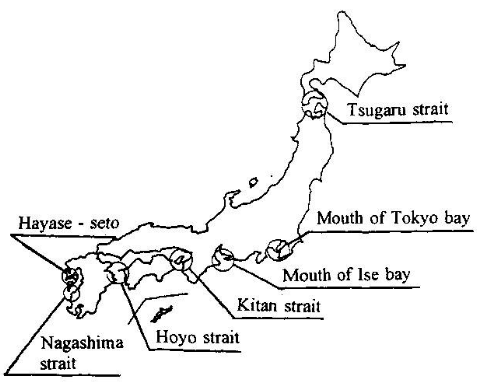


Fig. 2 Completed laying-down caissons

The anchorages are generally planned installed on land or on a beach, but depending on the project, some are at a depth of nearly 50m from the ground surface to the bearing layer and others are about 40m under the sea surface.

Trial calculations have been performed in order to study the limits of the water depth where it is possible to employ the laying-down caissons, and to devise measures to expand this range. For the trial calculations, the load of the superstructure was calculated assuming a suspension bridge as large as the Akashi-Kaikyo Bridge. The results are a vertical load of 130,000tf, a horizontal load of 3,800tf (corresponding to horizontal seismic intensity of 0.2), and moment of 380,000tf-m. The water depth were assumed to be 50m and 80m. The allowable bearing capacity of



Strait name	Distance from shore to shore	Maximum water depth
Tsugaru strait	East side : 13 km	270 m
	West side: 19 km	140 m
Mouth of Tokyo bay	15 km	80 m
Mouth of Ise bay	20 km	100 m
Kitan strait	11 km	120 m
Hoyo strait	14 km	200 m
Hayase - seto	5 km	120 m
Nagashima strait	2 km	70 m

the ground during an earthquake was assumed to be 150 tf/m^2. Past laying-down caisson foundations have all been cube shaped or column shaped with a 100% solid section. The deeper the water, the greater the dead load of a foundation, and possibly, a rise in the required section dimensions. For this reason, as shown in Figure 4, trial calculations were performed for 50% hollow section cubes and narrow top inverted T sections in addition to 100% solid section cubes. Figure 5 shows the foundations' plane dimension - maximum subgrade reaction relationships. If a 100% solid section cube foundation is installed where the water is 50m deep, the foundation's dead load will be high so that even if its plane dimensions are increased, the subgrade reaction will not be reduced very much. In order that the subgrade reaction be lower than the allowable bearing capacity, the plane dimensions must be 175m x 175m, which is unrealistic. In the case of a cube with a 50% solid section or an inverted T shaped foundation, the subgrade reaction force is lower than the allowable bearing capacity at plane dimensions of 60m x 70m.

As the results of the above trial calculations, where the water is deep, the foundation section should be reduced in order to lower the dead load of the foundation body. Based on these results, the authors have proposed the twin tower foundation and hollow rigid foundation shown in Figure 6 as improved versions of the older solid rigid type. The twin tower foundation is one that lowers the main tower itself directly to the sea bottom. In addition to the reduction effect of the concrete volume of the foundation body, it will provide superior seismic stability because its center of gravity is low and its inertia during an earthquake is small. Because the weight of this foundation is low in proportion to the area of its bottom surface, it can even be used on ground that is not hard. And because the area exposed to tidal currents and wave forces is small, it is very stable at normal times. A hollow rigid foundation is a conventional solid rigid type with a hollow space formed inside it. Where the bearing layer is good quality, it is possible to reduce the bottom slab of the foundation as shown in the figure, and it is also possible to sharply reduce the finished surface area of the sea bottom surface excavation.

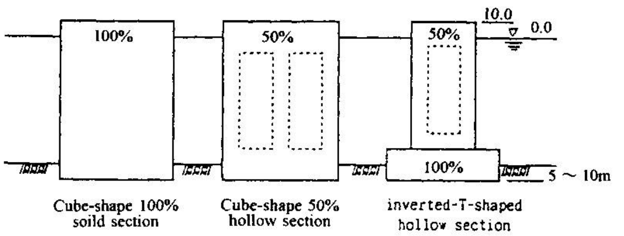


Fig. 4 Laying-down caisson used for the trial calculation

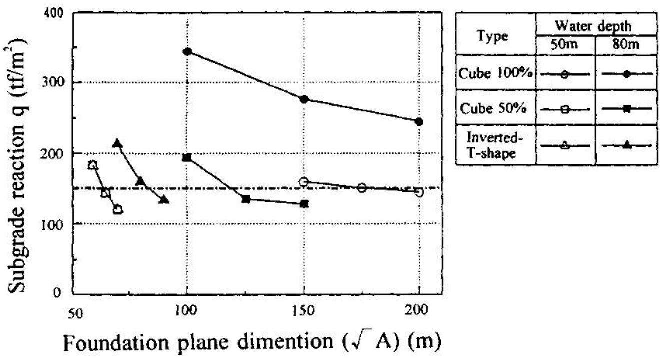
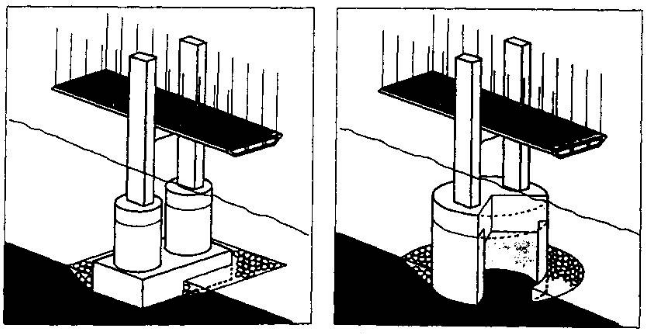


Fig. 5 Dimensions and subgrade reaction of a foundation



(a) Twin tower foundation (b) Hollow rigid foundation

Fig. 6 Proposed new foundations

3. Foundation design method

The selection of the bearing layer is an important factor to determine the construction costs. Because it is dependent to a large degree on the quantity of soil to be excavated to reach the bearing layer as well as on the dimensions of the foundation. In order to create a rational design in such cases, the bearing capacity and settlement of the foundation must be calculated with high precision and the results reflected in the design.

The twin tower foundation and hollow rigid foundation can both be categorized as shallow rigid foundations for design purposes. The bearing capacity and deformation calculation method of shallow foundations used to design ordinary bridges would present the following problems.
[1] The shear strength of the ground used in bearing capacity calculations is evaluated lower instead of ignoring its confining pressure dependency and strain level dependency.
[2] Because the modulus of deformation of the ground used in deformation calculations is a value obtained from plate loading test etc., the strain level of loading test does not conform with the strain in actual bridge foundations, and the deformation of the foundation is over-estimated.

In order to design a foundation with greater precision than in the past, it is necessary to use a calculation method that can account for these problems. One method under consideration would involve precisely modeling the physical properties of the ground at the site based on geological exploration and laboratory testing, and performing FEM analysis incorporating these properties to forecast the quantity of deformation of the foundation. The following is the specific procedure that would be used to do this.

[1] Clarification of the geological structure at the planned foundation location by carrying out boring, sonic prospecting and seismic velocity logging at the site.
[2] Using undisturbed specimens obtained by boring for precision laboratory testing to clarify the deformation properties of the ground including everything from the minute strain level to the failure range.
[3] Based on the results of [1] and [2], formulating the deformation properties of the ground to be used for numerical analysis by considering the confining pressure dependency and the strain level dependency.
[4] Performing calculations to determine the dimensions, load conditions, etc. of the foundation.
[5] Performing the numerical analysis in sequence according to the construction procedure in order to calculate the behavior of the foundation.

When the settlement of the Akashi-Kaikyo Bridge foundation was analyzed based on this procedure, the analytical and measured values coincided closely, confirming that the method is an effective way to forecast the settlement of a large foundation.

Next, an example of a trial calculation of a deep water main tower foundation performed with this method is described. The bridge used in the trial calculation is the suspension bridge shown in Figure 7. The water depth is 43m and the bearing layer is 10m below the sea bottom. The plane dimensions of the foundation were determined based on the dimensions necessary to fix the tower base to the foundation as well as on the space of two legs of the main tower. Figure 8 presents the results of the settlement forecast analysis of this foundation. The results of the analysis show that the foundation would subside very little, less than 4cm, under the load imposed when the bridge is completed, which is

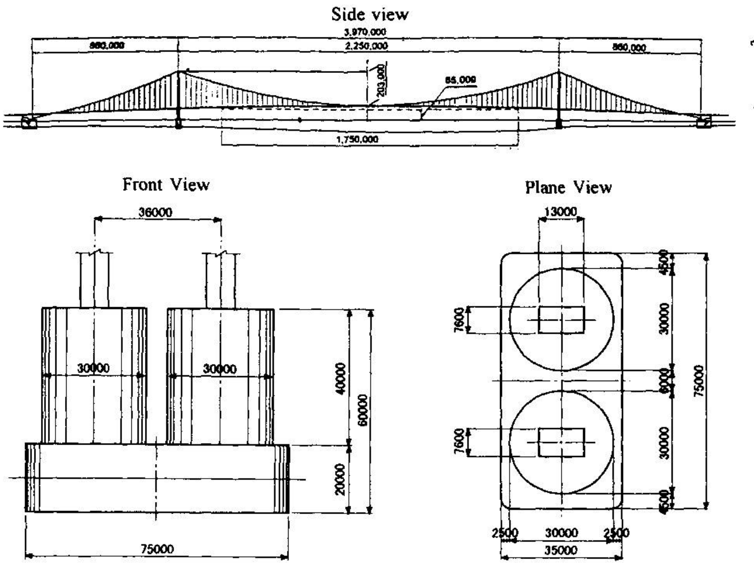


Fig. 7 Profile of bridge

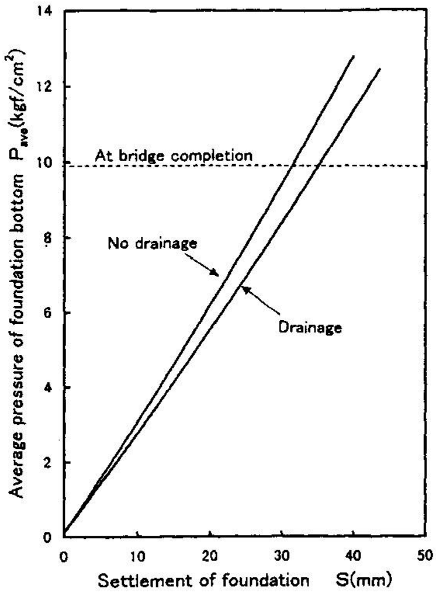


Fig. 8 Main tower foundation settlement forecast analysis

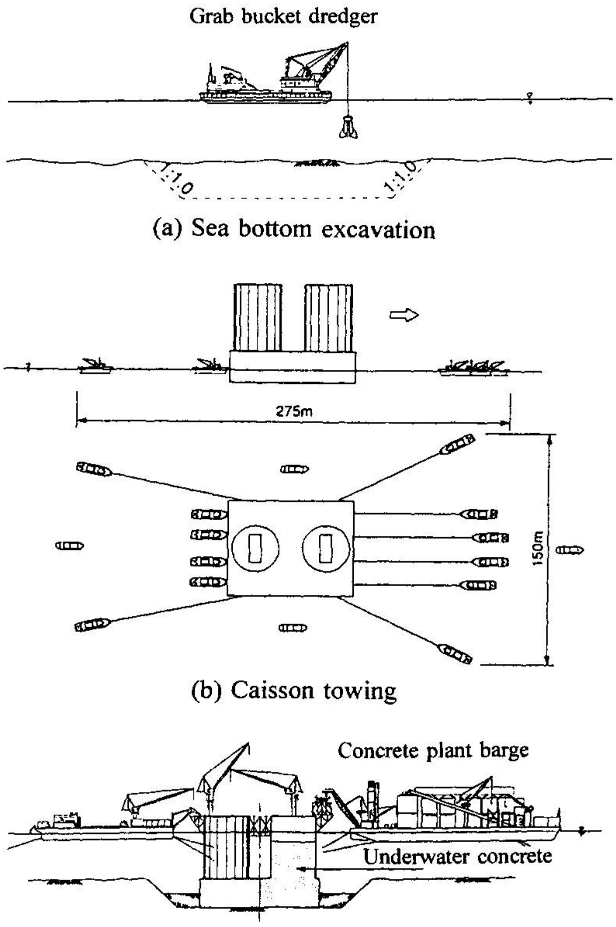


Fig. 9 Foundation execution procedure

little, less than 4cm, under the load imposed when the bridge is completed, which is sufficient for a suspension bridge foundation. The dimensions of this foundation would be far smaller than those of a conventional solid foundation, which would permit sharp reductions in both construction costs and the construction period. And a separate study of the stability of a foundation with these dimensions during an earthquake has confirmed that it satisfies the required safety level.

4. Foundation construction method

The construction methods for the new foundations proposed above were studied. The following paragraphs outline the problems studied in order to improve the construction method and construction efficiency, with the twin tower foundation used as an example.

[1] Sea bottom excavation (Figure 9 (a))
A grab bucket dredger is used to excavate the bottom down to the bearing layer. To shorten the construction period, the finishing surface area is reduced. When the

volume of excavation increases because the bearing layer is deep, consideration is given to discharging the excavated soil with an efficient pump boat. Because the work is performed in the ocean facing the open sea, a study is performed to select the type of boat that will guarantee a good working ratio.

[2] Fabricating and towing the caisson (Figure 9 (b))
After the caisson is fabricated at a dock, it is towed on the ocean surface to the foundation location. As a twin tower foundation, it is not as stable during towing as conventional foundations, but it is possible to guarantee stability with supplementary stabilizing techniques.

[3] Laying the caisson
After the towing operation is completed, mooring lines are connected to the caisson to adjust its location, then water is injected and it is installed at the fixed location.

[4] Foot protection
Foot protection is installed around the caisson by a clamshell dredger as a measure to prevent scouring, increase the resistance of the caisson's front surface, and to prevent mortar leakage.

[5] Casting concrete (Figure 9 (c))
After the interior of the caisson has been cleaned, underwater concrete is cast. A concrete plant barge is used to prepare the concrete. In order to provide underwater reinforced concrete, it is necessary to develop a casting method that permits the concrete to fill every part of deep water large cross section area foundations. As in the case of task [1]sea bottom excavation, the operating rate of the plant barge is improved.

[6] Main tower anchor frame installation
A crane barge is used to install the main tower anchor frame.

5. Conclusions

In order to realize the next generation projects that are now at the planning stage, it is necessary to construct deep water foundations under harsher conditions than those encountered at the site of the Honshu-Shikoku Bridge. To meet this need, deep water foundations constructed in Japan were surveyed, and a trial design was performed to study the application water depth limit and measures to raise this limit. The twin tower foundation and hollow rigid foundation were proposed as new types of foundations that will realize these projects now at the planning stage, and methods of design and construction of these two new foundations were studied.

The new foundations proposed in this report are improved versions of conventional foundations, so a radical new foundation concept will be a prerequisite to any further construction cost reductions. Furthermore, the above study looked at next generation projects for which specific studies have been undertaken and the deepest site in this group is about 70m. But projects that have not progressed beyond the conceptual stage include some that would face even more severe conditions, and in such cases, it will be necessary to expand preliminary studies to include, for example, the jacket type foundation.

In conclusion, the authors would like to express their sincere gratitude to the members of the Strait Highway Project Technology Committee that has already studied the technologies presented above.