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Development of New Foundation Method Using Steel Pipe Sheet Pile with High Strength Pipe-Junction "Hyper-Well SP"†

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Abstract:

A new steel pipe sheet pile composite foundation method called "Hyper-Well SP" was developed for application to a large-scale bridge. The structural characteristics and workability of the new method were verified in various experiments, and a design method was established. "Hyper-Well SP," which features high rigidity, was applied for the first time in the foundation of the Tokushima-Higashi-Kanjo-Ohashi, and construction of one section has already been completed. Workability equal to that of conventional sheet pipe sheet piles was confirmed in the construction of this actual foundation. Based on the results of the above-mentioned study, JFE Steel received certification for examination of construction technology from Public Works Research Center in Aug. 2004 as a new foundation method for large bridges, completing the development of this technology.

1. Introduction

In recent years, construction of the arterial highway system and access roads for airports and harbors has progressed throughout Japan. In these systems, bridges are frequently built on weak ground or in coastal areas, requiring large-scale foundations. There is also a strong desire for substantial cost reductions and shortening of the construction period in order to improve the effectiveness of investment in these projects.

To respond to the need for a significant reduction in the cost of large-scale foundations, JFE Steel developed the technology described in this paper as a method which improves economy by using an intrinsically high strength steel pipe-junction, while following the design and construction techniques used in conventional steel pipe sheet pile foundations[1–8].

2. Outline of "Hyper-Well SP Method"

Hyper-Well SP incorporates improvements in the conventional steel pipe sheet pile foundation method. The new method consists of two types, the normal type and a type with cast-in-place concrete piles.

(a) Normal type (**Fig. 1**)

Type in which the steel pipe sheet piles are driven to the bearing layer and high strength pipe-junctions are used in the pipe-junctions for the piles.

(b) Type with cast-in-place concrete piles (**Fig. 2**)

Type used in cases where there is a hard intermediate layer which would make pile-driving difficult and this intermediate layer cannot be expected to serve as the bearing layer; in such cases, steel pipe sheet piles using high strength pipe-junctions are placed as far as the intermediate layer, and cast-in-place concrete piles are constructed under every other pipe sheet pile.

This method comprises composite piles, which consist of a steel-concrete composite structure and cast-in-place concrete piles, and high strength pipe-junctions which mutually connect the piles. When compared with the conventional technology, these component elements

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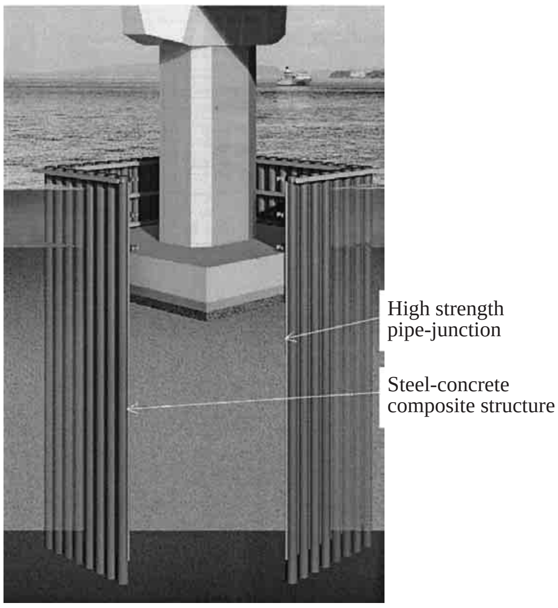

Fig. 1 Schema of Hyper-Well-SP (Normal)

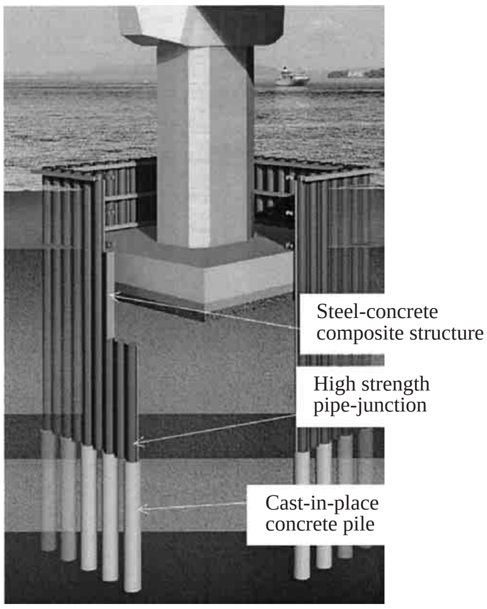

Fig. 2 Schema of Hyper-Well-SP (with Cast-in-place-concrete pile)

have the following features:

(1) High Strength Pipe-Junction

As shown in **Fig. 3** and **Photo 1**, the high strength pipe-junction is based on the P-P junction[9] used in conventional steel pipe sheet pile foundations, but the shear strength of the junction is greatly increased by the following structure:

(a) Bond strength with the mortar is increased by providing ribs on the inside surface of the junction pipe.

(b) Bond strength is also increased by using high strength mortar.

(c) A larger bond area is secured by increasing the outer diameter of the junction pipe from 165.2 mm to 267.4 mm. This increase in the junction pipe diameter also improves workability in washing inside the junction pipe.

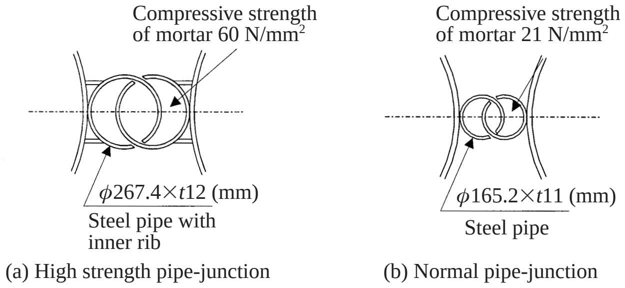

Fig. 3 Dimension of high strength pipe-junction

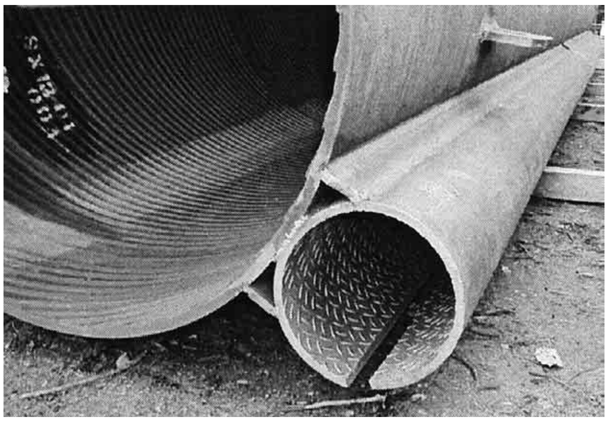

Photo 1 High strength pipe-junction pipe and steel pipe with inner rib

(2) Steel-Concrete Composite Structure

The steel-concrete composite structure is a structure consisting of a steel pipe filled with concrete. Effectiveness as a composite structure can be expected because ribs are provided on the inside surface of the pipe[10]. Accordingly, per-pile rigidity is higher than with steel pipes alone.

(3) Cast-in-Place Concrete Pile

Adoption of cast-in-place concrete piles in the bearing stratum part improves workability in comparison with driving steel pipe sheet piles deep into the bearing stratum. As a result, adequate embedment in hard ground is possible and a large bearing capacity can be secured. Field execution experiments and bending performance experiments of the junction between the steel pipe-concrete composite structure and the cast-in-place pile part confirmed the workability and performance of this part.

Because the rigidity of the foundation is increased by applying these component elements, the plane-view dimensions of the foundation can be reduced in comparison with conventional steel pipe sheet pile foundations. In other words, in large-scale bridges, where the plan dimensions of the foundation tend to be large with convention steel pipe sheet pile foundations, this is an excellent construction method with strong competitiveness in comparison with conventional steel pipe sheet pile foundations and furthermore, caisson foundations, which have an extensive record of use in large-scale bridges.

3. Construction Method with Hyper-Well SP

In this construction method, innovations were adopted in the junction pipe structure in order to achieve a large increase in the shear strength of pipe-junctions between the steel pipe sheet piles in comparison with conventional pipe-junctions, and the method of discharging soil from the junction pipe and filling the pipe with mortar was improved by applying a new construction technique. First, where the discharge of soil is concerned, in addition to the conventional water jet method, when the depth is great, the slurry discharge capacity is improved by combined use with a slurry discharge pipe with air lift, as shown in **Fig. 4**. The junction pipe spacing is maintained by increasing the outer diameter of the junction pipes to 267.4 mm and using spacers[4] in the junction parts, making it possible to secure the space comprised by the joint. As a result, it is possible to insert an air-lift slurry discharge pipe (e.g., outer dimension: 60.5 mm) into the junction pipe, thereby realizing effective construction.

In part of the junction pipe, connecting holes approximately 50 mm$W$ × 100 mm$H$ are provided intermittently in the pipe-junction longitudinal direction in order to accelerate the movement of soil to the slurry discharge pipe, which is set in a compartment in the center of the pipe-junction, and to facilitate mortar filling.

Next, as the construction procedure when using cast-in-place concrete piles (Fig. 2), after driving of the steel pipe sheet piles is completed, the interior of the main pipes of the sheet piles is excavated, and cast-in-place concrete piles are placed from the bottom of the piles[5].

These structures and construction techniques have been confirmed in field construction tests[4].

4. Shear Performance of High Strength Pipe-Junction

This chapter describes the results of tests to verify the shear performance of the high strength pipe-junction, which is one distinctive feature of this construction method, and the evaluation thereof.

In order to evaluate the shear performance of the high strength pipe-junction, test were performed using two specimens which were constructed in a field construction test[7] and two specimens[11] fabricated in the atmosphere (shop construction), using mortar strength as a parameter. The test conditions are shown in **Table 1**. These specimens were set in the testing machine by welding to the loading force column and reaction force columns, as shown in **Fig. 5**, and the shear performance of the junction connected to the two sides was evaluated by pressing the loading force column downward. Measurement items included the load, relative displacement of the joint, etc.

The relationship between the relative displacement and a value obtained by dividing the load by the total pipe-junction length (1.2 m × 2 = 2.4 m) is shown in **Fig. 6**. The test confirmed that all of the specimens possessed high strength on an order 10 times greater than that of the P-P junctions[12] used in conventional steel pipe sheet pile foundations. Moreover, there was no sizeable decrease in the load even when the specimens reached a large displacement, showing excellent deformation performance.

With the specimens constructed in the field construction test, part of the junction pipe was cut with a torch after loading and the mortar filling condition was inves-

Table 1 Condition of pipe-junction shear test specimen

Name	Condition of construction	Compressive strength of mortar (N/mm^2)
Test specimen ①	Field construction (in Ibaraki Pref.)	81.4
Test specimen ②	Field construction (in Chiba Pref.)	83.9
Test specimen ③	Shop construction	39.0
Test specimen ④	Shop construction	60.0

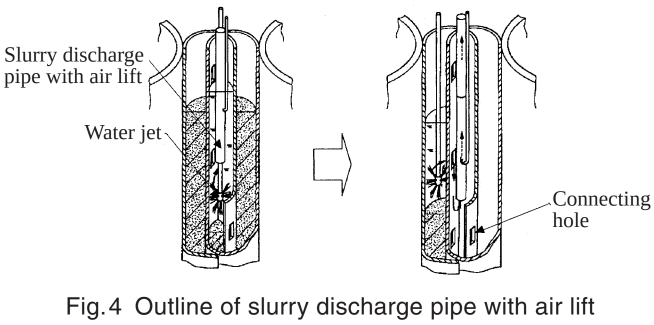

Fig. 4 Outline of slurry discharge pipe with air lift

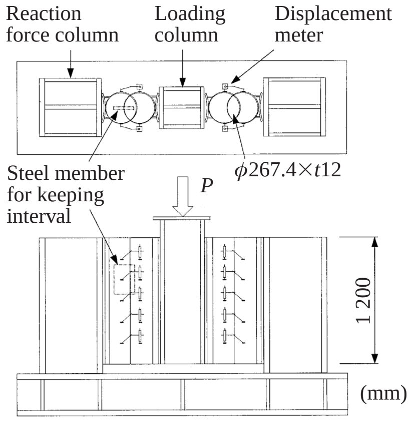

Fig. 5 Pipe-junction shear test specimen

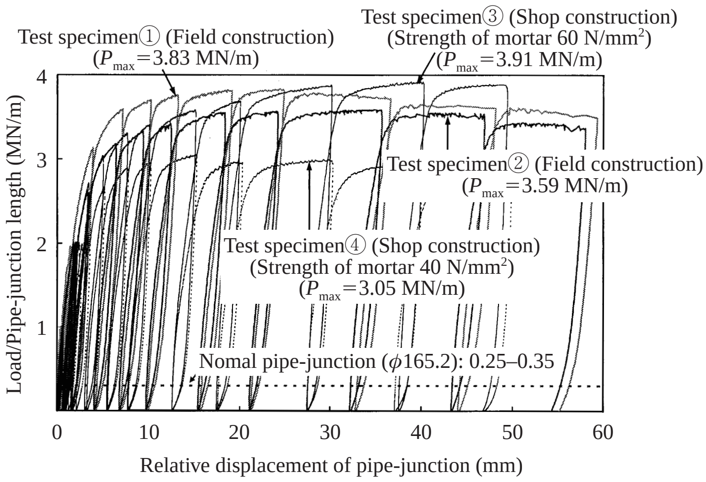

Fig. 6 Load and relative displacement curve

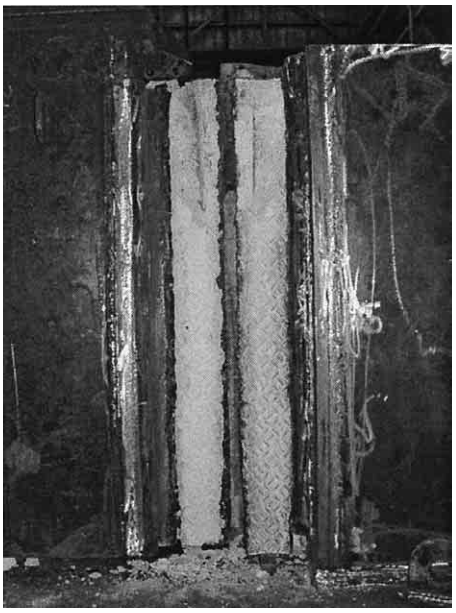

Photo 2 Appearance of mortar filling (Test specimen①)

tigated. An example of the results is shown in **Photo 2**. As estimated from the satisfactory results of the loading test, soil had been removed to the ribbed part of the inside pipe wall surface, and the junction pipes had been completely filled with mortar.

Next, in order to evaluate the effects of mortar strength and mortar placing conditions (i.e., under atmospheric condition, under water, under mud-water) on the shear strength of the high strength pipe-junctions, a study of the bond strength between the ribbed surface of the inside embossed steel pipe and the concrete, which is the primary factor determining the shear strength of the high strength pipe-junction, was carried out by a push-out test (**Fig. 7**)[11]. The test conditions are shown in **Table 2**. It may be noted that bentonite mud-water with a specific gravity of 1.04 was used as the mud-water condition, as this is the lower limit control value[13] for stabilization water of diaphragm walls. **Figure 8** shows the results of the relationship between the shear

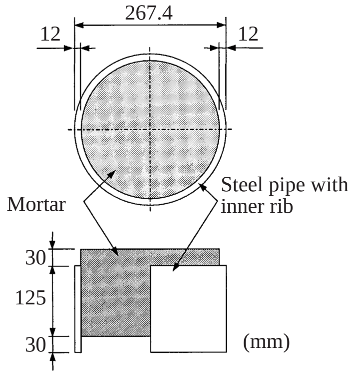

Fig. 7 Test specimen for push out test

Table 2 Quantity of test specimen for push out test

Condition of mortar pouring	Target strength of mortar			
	20 (N/mm²)	40 (N/mm²)	60 (N/mm²)	80 (N/mm²)
Atmospheric	–	2	–	2
Underwater	2	2	2	2
Under mud-water	–	2	–	2

strength estimated from the results of the bond test (bond strength multiplied by the effective bond surface for shear strength, as shown in **Fig. 9**) and mortar strength, together with the results of the above-mentioned pipe-junction shear test. It was found that shear strength increases as mortar strength increases, and shear strength in case of placement under mud-water shows

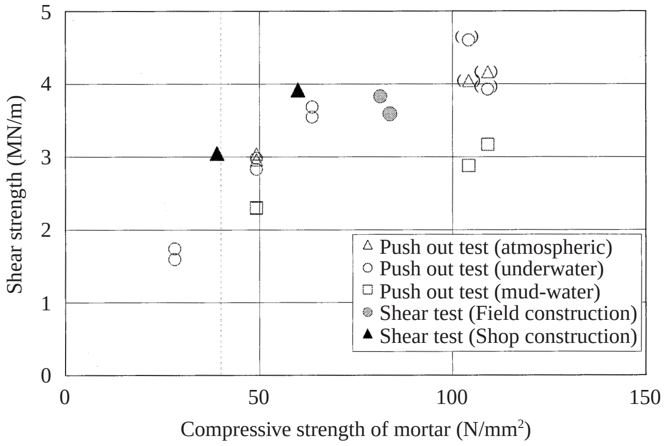

Fig. 8 Relation of shear strength and compressive strength

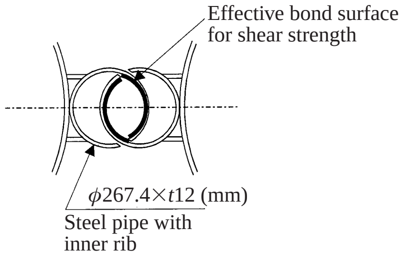

Fig. 9 Effective bond surface for shear strength

a small value in comparison with placement under an atmospheric condition or under water. Furthermore, these results also showed a good correspondence with the shear test results (in the case of field construction, considered to be close to placement under water). Thus, it was possible to confirm the appropriateness of this method of estimating shear strength based on bond strength.

In passing, it may be noted that, when the compressive strength test results of the samples (14 pieces) of high strength mortar (nominal strength: 60 N/mm^2; standard specification for high strength pipe-junction) sampled in the field construction test[4] were arranged in accordance with the conventional method[14], the average compressive strength of mortar with a nominal strength of 60 N/mm^2 was found to be 83 N/mm^2, and the lower limit of deviations was on the order of 40 N/mm^2.

Accordingly, assuming the lower limit value of 40 N/mm^2 as the specified concrete strength for the high strength mortar with a nominal strength of 60 Nmm^2, based on the fact that the compressive strength of the mortar in Fig. 8 is 40 N/mm^2, together with the value of shear strength when placement under mud-water is assumed, the design value (minimum value: Type-A) of the shear strength of the high strength pipe-junction was put at 2.0 MN/m.

Here, if the strength of the high strength pipe-junction is set low in the design, the evaluation will be excessively conservative for many items, for example, the amount of horizontal displacement of the top of the foundation, the maximum bending moment generated in the steel pipe sheet pile, and so on. On the other hand, however, there are also cases where calculations will give an excessively small bending moment acting on the cast-in-place pile part (when the cast-in-place concrete pile type is used). Therefore, a second shear strength design value of 4.0 MN/m (Type-B) was given for the high strength pipe-junction, this being somewhat larger that the result in the shear test, and design verification was carried out using these two types of shear characteristics (**Fig. 10**). Here, the design value of stiffness for the high strength pipe-junction was set at 1 200 MN/m^2, considering the experimental results.

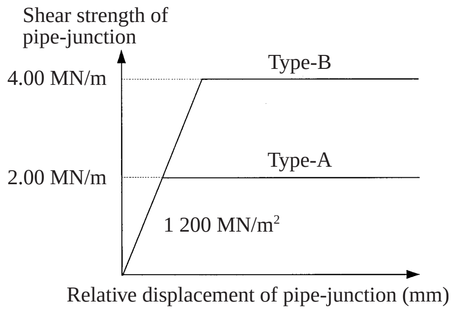

Fig. 10 Analysis model for shear character of pipe-junction

5. Design Method

5.1 Design of Normal Type (Fig. 1)

With the normal type of Hyper-Well SP, the section forces, displacement, and ground reaction are calculated by the equivalent well beam method[15], which considers the shear deformation of the pipe-junctions. As the shear characteristics of the high strength pipe-junctions, two types (Type-A and Type-B) were used, based on the experimental results presented in Chapter 4.

5.2 Design of Cast-in-Place Concrete Pile Type (Fig. 2)

In designing Hyper-Well SP foundations with cast-in-place concrete piles, a correct analysis of the behavior of the cast-in-place concrete pile part is necessary. Therefore, the section forces, displacement, and ground reaction are calculated using a stereo frame model. In the stereo frame model, as shown in **Fig. 11**, the analysis is performed by modeling the steel pipe sheet piles (steel-concrete composite structure) and the cast-in-place piles as beam elements, and the high strength pipe-junctions and ground resistance as spring elements.

In the high strength pipe-junctions, in addition to the shear characteristic (spring model) in the vertical direction, as mentioned in connection with the design of the normal type, the compressive/tensile spring between the steel-concrete composite structures, horizontal-direction shear spring, and rotation spring around the member axis are also considered. These are set based on respective element experiments[11].

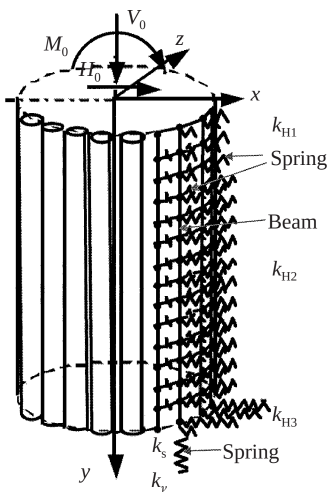

Fig. 11 Stereo flame model for analysis

6. Adoption in Tokushima-Higashi-Kanjo-Ohashi

This technology was adopted for the first time in the Higashi-Kanjo-Ohashi (tentative name) which Tokushima Pref. is constructing at the mouth of the Yoshino River. Substructure construction of this bridge began in Dec. 2003, and construction has already been completed in one work section. For the bridge, a "standing style" foundation method was selected, as shown in **Fig. 12**[16]. Therefore, from the viewpoint of minimizing the river flow impediment ratio, a flattened oval plan-view shape was necessary. As a result, as shown in **Fig. 13**, conventional pipe-junctions were used in the circumference part, and high strength pipe-junctions were used in the partition wall part. The relationship between the soil profile and the length of the installed foundation is shown in **Fig. 14**. As plans called for driving steel pipe sheet piles with a total length of 55 m to an 8 m root depth in a sand-and-gravel layer, which was to be used as the bearing layer, these can be considered difficult construction conditions for steel pipe sheet piles. Two steel pipe sheet piles were joined longitudinally, and the piles were driven with a vibro hammer until the upper pile was partially embedded. Driving was then continued with a hydraulic hammer (ram weight: 115 kN, maximum pile-driving energy; 203 kN·m). A view of the construction work is shown in **Photo 3**.

Four steel pipe sheet piles each were selected for the high strength pipe-junctions and conventional pipe-junctions, and the blow count and driving depth in the bearing layer were measured. The results are shown in **Table 3**. In spite of some individual differences, on average, no meaningful difference could be observed between the two methods.

Next, to confirm the effect of the difference in the pipe-junctions on construction accuracy, the plane position of the steel pipe sheet piles shown in Fig. 13 after completion of pile driving was measured in two direc-

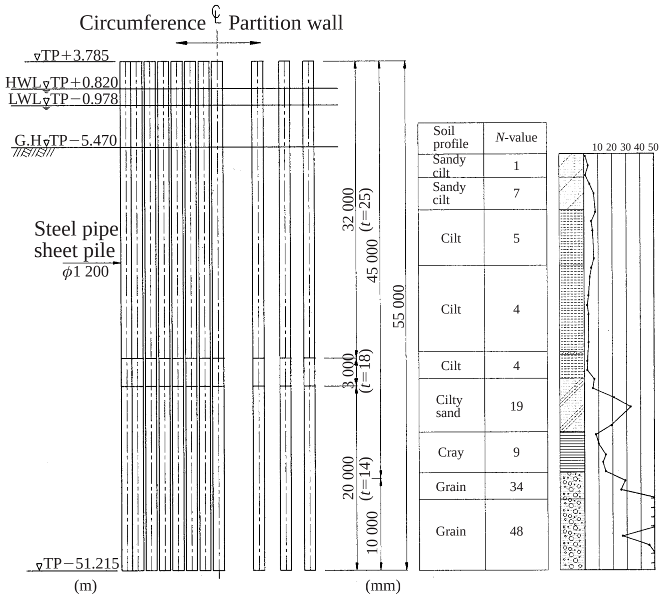

Fig. 14 Soil profile of foundation site

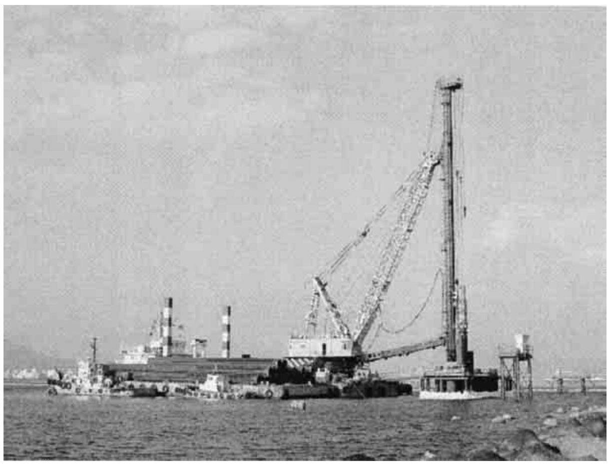

Photo 3 A view of construction

Table 3 Blow count and driving depht in bearing layer

	Number	Blow count in bearing layer		Driving depth in bearing layer (mm/1 blow)	
High strength pipe-junction	①	1 316	Average 1 154	7.1	Average 6.6
	②	1 004		6.8	
	③	1 299		6.5	
	④	995		5.9	
Normal pipe-junction	①	1 088	Average 1 194	8.1	Average 7.9
	②	1 066		8.2	
	③	1 533		6.3	
	④	1 088		8.9	

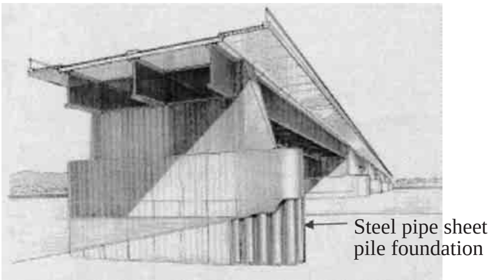

Fig. 12 Pier foundation (standing style)

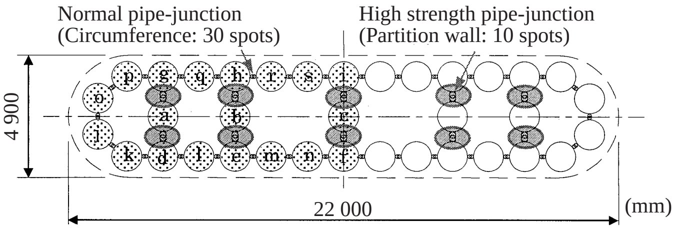

Fig. 13 Cross section of steel pipe sheet pile foundation

Table 4 Eccentricity of steel pipe sheet pile

Pile	Junction form	Average eccentricity (mm)	
		Longitudinal direction	Transverse direction
a–c	High strength pipe-junction: 2 spots	23	15
d–i	High strength pipe-junction: 1 spot Normal pipe-junction: 2 spots	26	26
j–s	Normal pipe-junction: 2 spots	22	11

tions, the bridge longitudinal direction and transverse direction. The results are shown in **Table 4**. In this regard as well, there was no large difference between the high strength pipe-junction and the conventional pipe-junction. The results of the above-mentioned measurements confirmed that the workability of the steel pipe sheet piles with the high strength pipe-junction is equal to that of steel pipe sheet piles with conventional pipe-junctions.

7. Conclusion

JFE Steel developed a new construction method for steel pipe sheet pile foundations called “Hyper-Well SP,” which features a new high strength pipe-junction. By substantially increasing rigidity, the new method makes it possible to reduce the plane dimensions of foundations for large-scale bridges. As described in this paper, the structural performance and workability of the new method were studied, and a design evaluation method was established. Based on the results of this study, JFE Steel received certification for examination of construction technology from the Public Works Research Center in Aug. 2004 as a new foundation method for large-scale bridges. Study supporting further adoption, including case studies under various conditions, is planned for the future.

In closing, the authors wish note that this work was carried out as joint research with two construction companies, Shimizu Corp. and Obayashi Corp. We wish to express our deep appreciation to all concerned at both companies.

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