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Wide Steel Sheet Piles

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Abstract

The Japanese government has set up an action plan to reduce the total cost of public works construction projects from planning to execution by 10% or more. To help reduce construction costs and dissolve the difficulty in distinguishing a standard type from an improve type, Nippon Steel Corporation, NKK, Kawasaki Steel Corporation, and Sumitomo Metal Corporation engaged in research and development to widen steel sheet piles in 1995, and thereafter produced and marketed them in April 1997. This report describes how the wide steel sheet piles were developed, what their features are, and provides a summary of the performance assurance test.

1. Introduction

Nippon Steel, NKK, Kawasaki Steel, and Sumitomo Metal Industries started the development of wide steel sheet piles in fiscal 1995 for the purpose of contributing to the cost reduction of public works projects and began the production and sale of the wide steel sheet piles in April 1997. The development history, features, structure, and construction performance validation testing of the wide steel sheet piles are reported in this paper.

2. History and Features of Steel Sheet Piles

Japan's steel sheet piles have a history of about 70 years, starting with the U-shaped steel sheet piles produced at what was then the government-owned Yawata Iron & Steel Works in 1931. Steel sheet piles of the Lackawanna type (double-jaw type) were initially manufactured. In 1960, the process of rolling steel sheet piles of the Larssen type (present standard jaw type) was developed. In 1963, improved U-shaped steel sheet piles were added. Today, U-shaped steel sheet piles are manufactured only in the Larssen type. The steel sheet pile method has rapidly spread and developed thanks to the combination of the development of excellent technology for rolling large amounts, establishment of various design standards, and development of construction technology in response to specific site conditions. It is now an indispensable construction method in harbor, river, earth retaining, foundation, and many other projects.

Steel sheet piles have the following characteristics:

(1) Easy to install and do not require large construction equipment.
(2) Can be rapidly driven in a very short time.
(3) Profile and length can be changed to meet specific site conditions, so that their walls can be efficiently and economically designed.
(4) Walls are light in weight and are advantageous over gravity walls in a seismic design.
(5) Watertightness allows seepage control work.

3. Development Background and Technical Problems of Wide Steel Sheet Piles

3.1 Development background

Steel sheet piles have not undergone large changes in their profiles since the start of their commercial production and are still mainstream construction materials for earth retaining walls. This is because steel sheet piles are mature products that can meet various needs, including rapid restoration of harbor and river facilities after disasters. In recent years, the progress of construction technology utilizing the steel sheet pile method has prompted the development of steel sheet piling machines with low vibration and noise, and has also increased the driving power of steel sheet piling machines. Con-

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struction projects in harbors and other deep water areas now require longer steel sheet piles. Such conditions have combined to impose demanding requirements for steel sheet piles strong enough to withstand severe driving.

Japan's economy has been in a recession. The Japanese government formulated the "Action Guidelines Concerning Measures for Cost Reduction of Public Works" at a meeting of concerned ministers on April 4, 1997. The guidelines aim at reducing by 10% or more the total cost of public works projects from their planning through construction phases.

The five integrated steel manufacturers set about developing wide steel sheet piles to meet the above-mentioned construction needs as well as the new issue of cost reduction. Their development efforts also sought to eliminate the complexity of selectively using standard types (II to IV) and improved types (I_A to IV_A) of steel sheet piles by consolidating them into a wide steel sheet pile series.

3.2 Determination of sectional profiles

The profile design of wide steel sheet piles took the following requirements into consideration:

(1) They should be lower in material and construction costs than conventional steel sheet piles.

(2) They should be of such profile that they can be produced by making the most of existing mill equipment without unit price increase due to extensive equipment modification.

(3) They should be as easy to drive as conventional steel sheet piles.

The steps taken to determine the final profile of wide steel sheet piles are described below.

Wide steel sheet piles decreased the steel weight per unit wall area and increased the section performance per unit steel weight as compared with conventional steel sheet piles (see **Fig. 1**) Given the manufacturing limits of existing production facilities, the effective width was set at 600 mm as already adopted for European counterparts. Three types (II_W, III_W, and IV_W) were selected from among those types that had section properties in greatest demand. To facilitate construction, the effective depth was made greater than that of conventional steel sheet piles to raise section stiffness per pile. The thickness of section parts was determined to prevent stress concentration during driving and deformation due to repeated use. The profile of each type was also designed to ensure stable piling. Wide steel sheet piles were made as easy to install as conventional steel sheet piles by setting the angle of swing and interchangeability as required during construction. The advantage of reducing the required number of piles by two-thirds compared with conventional 400-mm wide steel sheet piles was fully used. The section profiles of wide steel sheet piles thus determined are shown in **Fig. 2**.

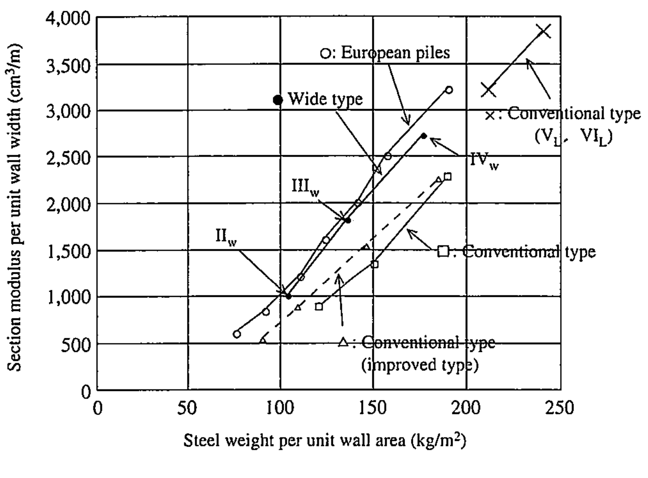


Fig. 1 Relationship between steel weight and section performance

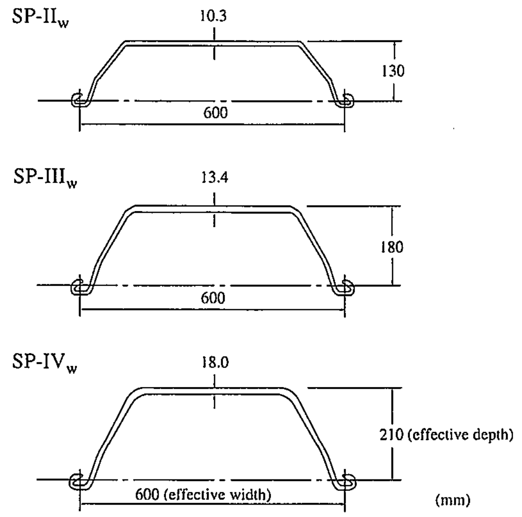


Fig. 2 Sectional profiles of wide types (SP: sheet pile)

3.3 Technical problems with increased width

To achieve the above-mentioned concept of increased width in terms of design, it is necessary to verify the section performance of the wide steel sheet piles at member level. It is also necessary to validate by in-situ lateral load testing the joint efficiency required when designing general-purpose steel sheet pile walls. In terms of construction, it is necessary to confirm by ground condition and construction method that the wide steel sheet piles are as easy to install as the conventional steel sheet piles.

4. Design Technology

4.1 Design methods

Wide steel sheet piles for wall applications can be designed by the same method as conventional steel sheet piles. Section performance for use in corrosion-resistant design is given in charts prepared by type of wide steel sheet pile (see the technical documents of the Steel Sheet Pile Technical Committee, Japanese Association for Steel Pipe Piles, and the catalogs of wide steel sheet pile manufacturers). The section modulus reduction factor for corroded piles is practically the same for both wide and conventional steel sheet piles (see **Table 1**). Focusing on the corrosion allowance of 2 mm ($t_1 = t_2 = 1$ mm) in river applications ($\alpha = 1.00$), the section modulus reduction factor is 81, 85, and 88% for the types II_W, III_W, and IV_W of wide steel sheet piles, respectively. These values are almost the same as the 81, 85 and 87% for the types II, III, and IV of conventional steel sheet piles, respectively.

4.2 Structural performance

4.2.1 Member structure tests

To investigate their section performance, the wide steel sheet piles were compression- and bend-tested.

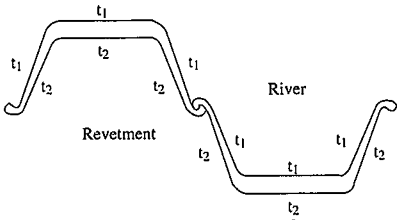
(1) Compression testing

(a) Purpose

When the tip of a driven steel sheet pile reaches a soil having a standard penetration test value (N-value) of about 30, the penetration resistance of the soil may sometimes increase and cause the buckling of the steel sheet pile. The wide steel sheet piles were compres-

Table 1 Section modulus reduction factor for corroded piles

Type		Corrosion ratio $\alpha = t_2/t_1$ (%)				
		1.00	0.75	0.50	0.25	0
Wide	II_w	81	83	86	88	90
	III_w	85	87	89	90	92
	IV_w	88	90	91	93	94
Conventional	II	81	83	85	88	90
	III	85	87	89	90	92
	IV	87	88	90	92	93



Z: Section modulus for corroded pile (cm^3/m)
Z_0: Section modulus for noncorroded pile (cm^3/m)
Z/Z_0: Section modulus reduction factor for corroded pile (%)
t_1, t_2: Corrosion thickness on both side of pile (mm)
α: t_2/t_1 ratio

sion tested to investigate their compressive strength by estimating the compressive force applied to them during construction.

(b) Overview

The compression test is illustrated in **Fig. 3**. Since the compressive load was not considered to act always at the center of the cross section of the pile during actual construction and an eccentric load was likely to act on the pile instead, specimens were compression tested in three loading patterns as shown in **Table 2**. The specimens were 1-m long, type III_W wide steel sheet piles.

(c) Results

The relationship between the load and axial displacement of the specimens is shown in **Fig. 4**. This figure also shows the end yield loads calculated which allow for the bending moment due to the product of the eccentric distance and the axial force for eccentric axis compression and the full-section yield load calculated for central axis compression, based on the yield values obtained by material tests. As confirmed in the figure, the wide steel sheet piles have a load-bearing capacity higher than the theoretical yield load in all of the loading patterns considered.

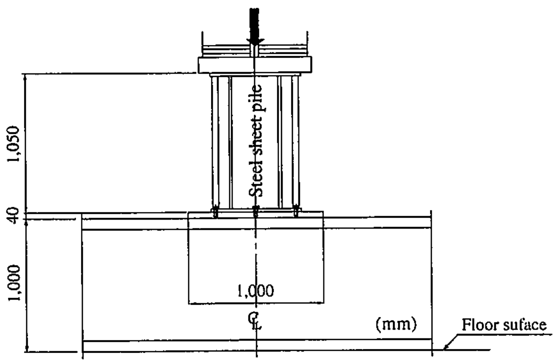
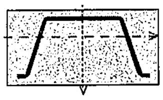
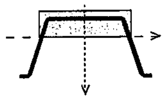
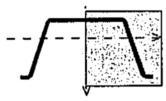


Fig. 3 Schematic illustration of compression test

Table 2 Loading patterns in compression test

Loading pattern	Compression part
Central axis compression	
Eccentric compression of web area	
Eccentric compression of flange area	

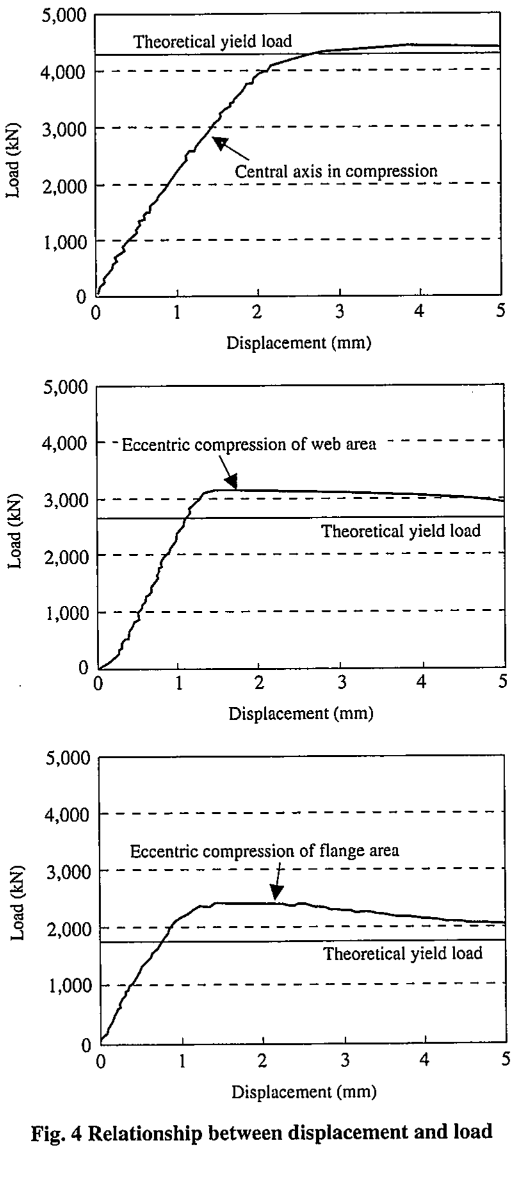


Fig. 4 Relationship between displacement and load

(2) Bend testing
(a) Purpose

The bending resistance (geometrical moment of inertia) of the wide steel sheet piles was investigated.

(b) Overview

The bend test is illustrated in **Fig. 5**. The wide steel sheet pile (type III_w) rests as a simple beam at two supports and is loaded at two points equally spaced from each support. The specimen was loaded by the two methods shown in **Table 3** to investigate the effect of the bending direction.

(c) Results

Fig. 6 shows the ratio (I/I_0) of the geometrical moment of inertia (I) calculated from the strain, measured with a strain gauge attached to the center of the specimen, to the theoretical geometrical moment of inertia (I_0). Regardless of the bending direction plane, the calculated value was 90% or more of the theoretical value. The measured value was smaller than the theoretical value for some specimens. When bend-tested in air, the sheet piles increased in width at the joints and decreased in depth, reducing the geometrical moment of inertia. Since sheet piles are interlocked to form a wall in an actual application and therefore, are not deformed in wide direction in the joints, they are believed to have a geometrical moment of inertia close to the theoretical value.

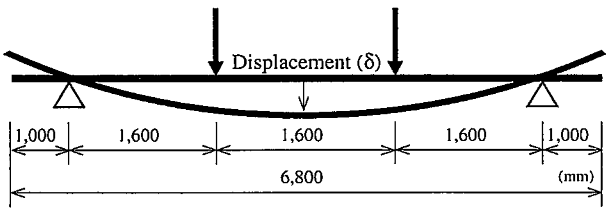
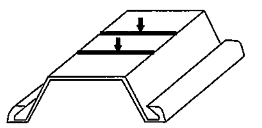
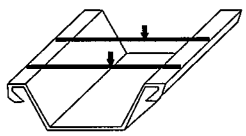


Fig. 5 Schematic illustration of bend test

Table 3 Loading types in bend test

Loading plane	Loading direction
Web	
Joint	

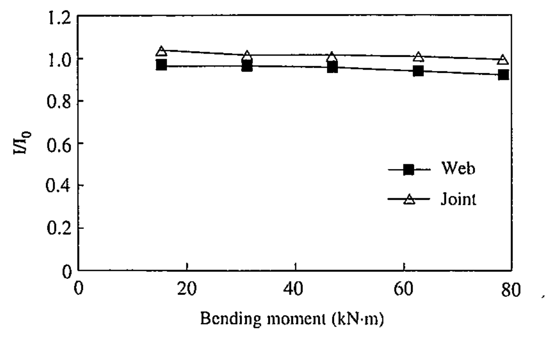


Fig. 6 Relationship between bending moment and geometrical moment of inertia

4.2.2 In-situ lateral loading test for joint efficiency
(a) Purpose

U-shaped steel sheet pile walls have their joints positioned at the wall center line. When the joints are displaced by the bending load arising from the earth pressure, for example, the U-shaped steel sheet pile wall may have lower section performance than when it behaves as an integral wall. The design of some U-shaped steel sheet pile walls sets the reduction factor by which to multiply the section performance to obtain the joint efficiency. The wide steel sheet piles were in-situ lateral load-tested to investigate their joint efficiency.

(b) Overview

The test used four wide steel sheet piles (type III_w) and six conventional steel sheet piles (type III). The wide steel sheet piles and the conventional sheet steel piles were driven to the same wall width of 2.4 m. The length projecting above ground was 1.8 m, and the pile head was restrained by a concrete cap. As shown in **Fig. 7**, two horizontal jacks were installed at 1.6 m above ground and were used to load both the wide steel sheet pile wall and the conventional steel sheet pile wall at the same time. A beam was attached across each wall to uniformly load the concrete cap.

(c) Results

Focusing on the lateral deflection of the sheet pile head, the joint efficiency with respect to the geometrical moment of inertia was calculated by analysis. The analysis assumed a joint efficiency of 0.8 with respect to the geometrical moment of inertia and was performed for two cases: case a) for linear soil resistance and case b) for nonlinear soil resistance.

a) Linear analysis

The results of analysis using the linear subgrade reaction model shown in **Fig. 8** are compared with the test results in **Fig. 9**. The linear subgrade reaction model has an imaginary ground surface set at a position where the active earth pressure equals the passive earth pressure according to the design method specified for self-standing steel sheet piles in the "Design Procedures for Disaster Restoration Work" of the Ministry of Construction. Since steel sheet piles are commonly used where the maximum strain developed is about 300 μm, the analysis was conducted in the load region where the strains observed in the test steel sheet piles was 300 μm or less. The analysis results almost agree with the test results for conventional steel sheet piles. Their joint efficiency with respect to the geometrical moment of inertia is estimated at about 0.8. For the wide steel sheet piles, the measured deflection is smaller than the calculated deflection, and the joint efficiency with respect to the geometrical moment of inertia is estimated at 0.8 or more.

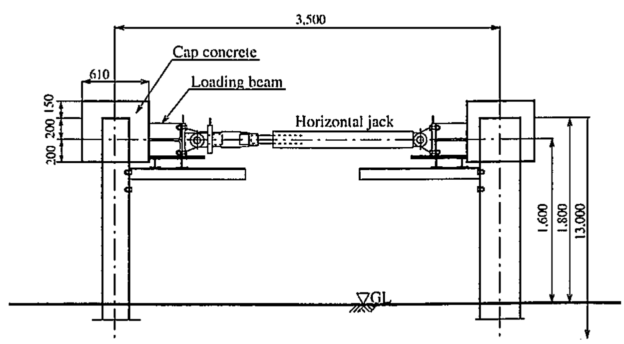


Fig. 7 Schematic illustration of on-site lateral loading test

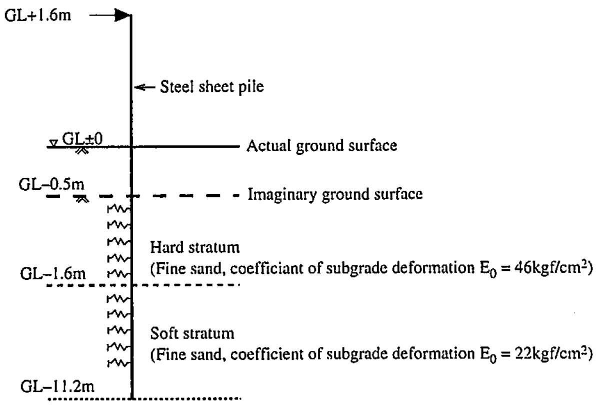


Fig. 8 Linear subgrade reaction model

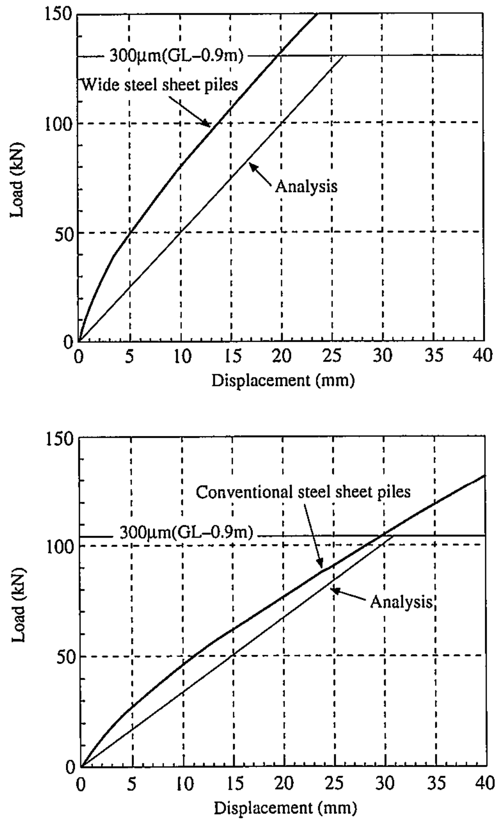


Fig. 9 Results of linear analysis

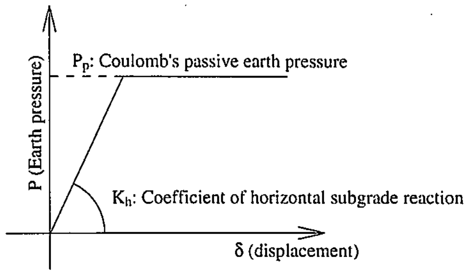


Fig. 10 Nonlinear subgrade reaction model

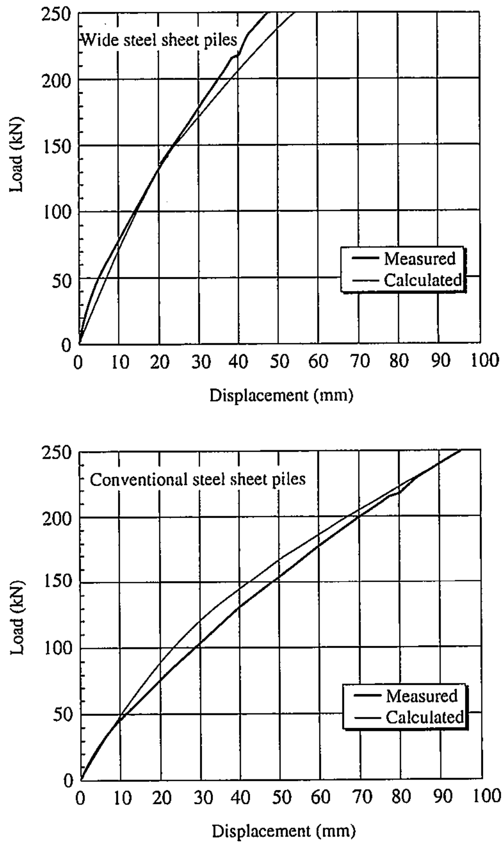


Fig. 11 Results of nonlinear analysis

b) Nonlinear analysis

Nonlinear analysis was performed using a bilinear elastic-plastic model that assumes that the passive earth pressure is the upper limit of the subgrade reaction as shown in **Fig. 10**. The analysis results are compared with the test results in **Fig. 11**. The analysis results fairly agree with the test results for both the wide steel sheet piles and the conventional steel sheet piles. The joint efficiency with respect to the geometrical moment of inertia is estimated at about 0.8 for both types. The analysis results agree well with the test results also in the load range where the nonlinearity of the soil is intensified as compared with the linear analysis.

These findings suggest that the joint efficiency of the wide steel sheet piles can be considered almost identical to that of the conventional steel sheet piles.

5. Construction Technology

5.1 Development targets

(1) Wide steel sheet piles should be capable of being driven by the same construction methods as employed for conventional steel sheet piles.

Wide steel sheet piles can be driven by the most commonly used vibratory hammer driving and pressing methods.

(2) Wide steel sheet piles should be as easy to install as conventional steel sheet piles.

Wide steel sheet piles are similar to conventional steel sheet piles in terms of construction work efficiency, completed work quality, noise, vibration, and other factors.

(3) Wide steel sheet piles should be interchangeable with conventional steel sheet piles.

The joints of the wide steel sheet piles can engage those of conventional steel sheet piles. This development target was met by selecting joint profiles that can interlock with conventional steel sheet piles.

5.2 Development items

5.2.1 Adaptation to construction methods and machines

(a) Vibratory hammer driving method: Since existing vibratory hammers (electric and hydraulic) can be used, their capability to install wide steel sheet piles should be verified.

(b) Pressing method: Wide steel sheet piles require special pressing machines because their cross-sectional profiles differ from conventional steel sheet piles. Special pressing machines should be developed in cooperation with specialized companies and their capability to install wide steel sheet piles should be validated.

5.2.2 Verification of construction performance

The construction time, completed work quality, noise, vibration and other factors should be investigated by changing the construction method, steel sheet pile type, steel sheet pile penetration depth, ground conditions, and other variables. The construction performance of the wide steel sheet piles should be validated.

5.3 Construction performance validation tests and evaluation

5.3.1 Preliminary validation tests

The preliminary validation tests listed in **Table 4** were carried out prior to use in actual projects. The soil conditions and results of the Nos. 1, 2, and 5 tests are shown in **Figs. 12 to 14**. Wide steel sheet piles being driven in the No. 1 test is shown in **Photo 1**. In these tests, the driving time and the current value was measured at intervals of 1 m to observe the vibratory hammer load. The driving time was about 20% shorter for type III_W in the sandy soil of the No. 1 test and was approximately the same for both type III_W and type III in the cohesive soil of the No. 2 test. The current value was about 15% and 25% greater for type III_W in the Nos. 1 and 2 tests, respectively. In the No. 5 test, the type III_W was driven by a special pressing machine which was confirmed to have satisfactory construction performance. A type III_W pile being driven in the No. 5 test is shown in **Photo 2**.

5.3.2 Construction performance investigation tests in actual projects

The construction performance investigation tests listed in **Table 5** were conducted in actual projects. Structural sections and boring logs are shown in **Figs. 15 to 17**.

No. 1 is a river revetment project in Hokkaido. The driving time was about 6 min per pile, and 18.6 piles were installed per day on average. The noise at a distance of 30 m was 75.6 dB-A (45 kW) and 75.4 dB-A (60 kW), and the vibration at the same distance was 74.5

Table 4 Preliminary validation tests

No.	Steel sheet pile data			Construction method and machine	Ground condition
	Type	Length	Penetration depth		
1	III_w	15m	14m	Vibratory hammer driving	Sandy soil
	III	15m	14m	60kW	
2	III_w	15m	14m	Vibratory hammer driving	Cohesive soil
	III	15m	14m	90kW	
3	III_w	15m	14m	Vibratory hammer driving	Alternate strata of
	III	15m	14m	60kW	sandy and cohesive soil
4	III_w	10m	9m	Vibratory hammer driving	Gravel and cohesive soil
	III	10m	9m	90kW	
5	III_w	15m	14.5m	Hydraulic presssing	Alternate strata of
				Maximum capacity of 150tf	sandy and cohesive soil

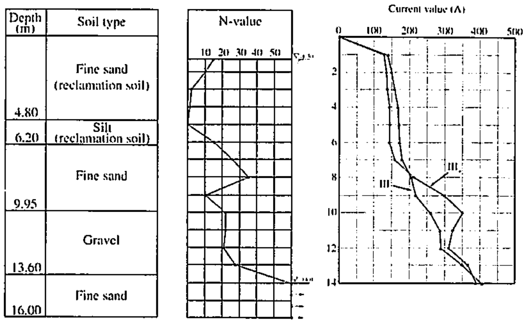


Fig. 12 Preliminary validation test (No. 1)

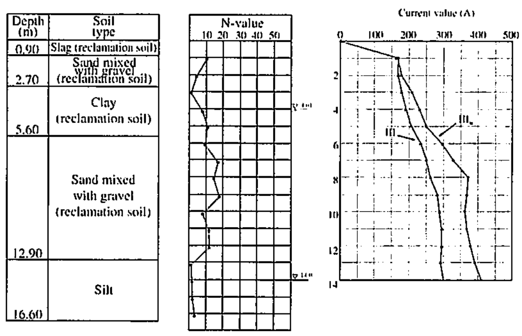


Fig. 13 Preliminary validation test (No. 2)

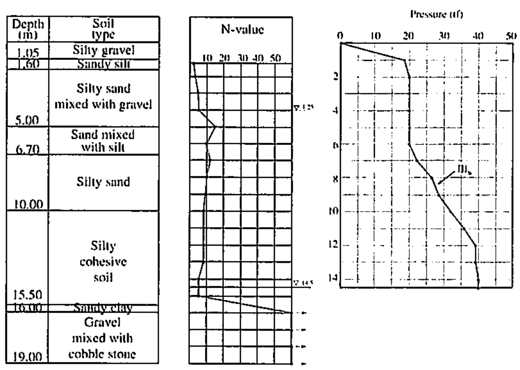


Fig. 14 Preliminary validation test (No. 5)

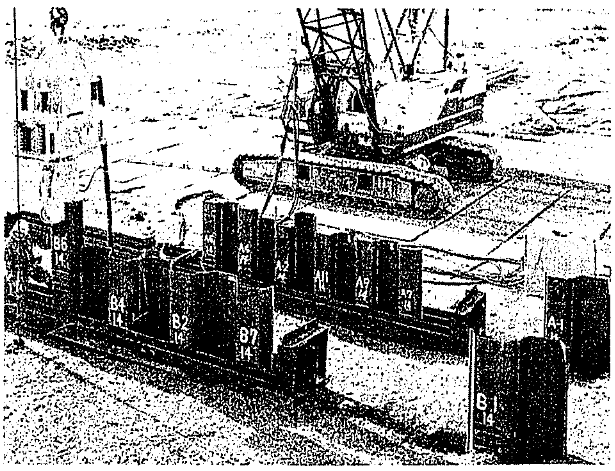


Photo 1 Piles being installed in preliminary validation test (No. 1)

dB (45 kW) and 72.2 dB (60 kW).

No. 2 is a river closing dike project in Fukuoka Prefecture. The driving time was about 10 min per pile, and 21.2 piles were installed per day on average. The noise and vibration at a distance of 30 m were 73.0 dB-A and 55.7 dB, respectively.

No. 3 is a flood way project in Tochigi Prefecture. Types III_w and IV were comparatively drive-tested. The test results are given in **Table 6**. Under the same construction machine conditions, the driving time per pile was 14 to 25% longer at site A for type III_w than type IV and was 5 to 17% shorter at point B for type III_w than type IV. Although the soil at site B was harder, the driving time was practically the same for both types. Despite the extremely hard soil, the pile deformation after driving and extraction was small for both types and fully met the JIS tolerances of ±4% for the overall depth and –5 mm and +10 mm for the overall width. Type III_w was practically the same as type IV in vibration. Type III_w produced slightly larger noise under the same construction machine conditions. The noise was initially

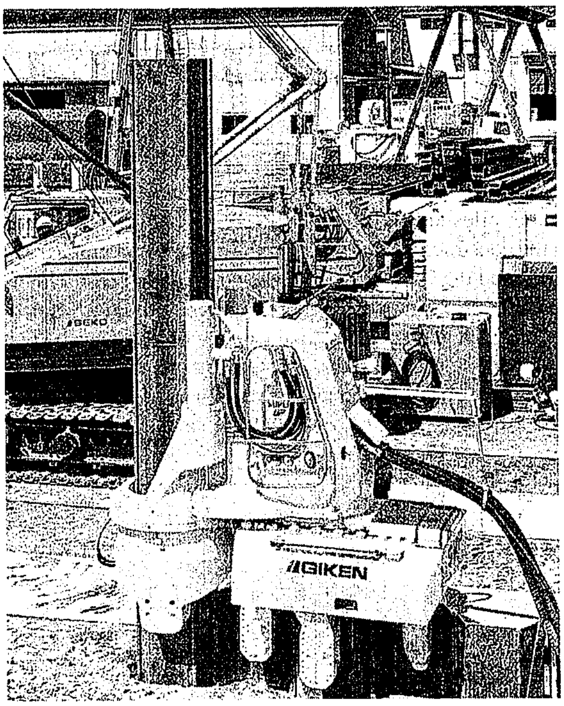


Photo 2 Piles being installed in preliminary validation test (No. 5)

Table 5 Construction performance investigation tests in actual projects

No.	Steel sheet pile data			Construction method and machine	Ground condition
	Type	Length	Penetration depth		
1	III_w	13m	12m	Vibratory hammer driving 45kW, 60kW	Cohesive soil
2	III_w	18.5m	13.5m	Vibratory hammer driving 60kW	Sandy soil
3	III_w IV	14m 14m	13m 13m	Vibratory hammer driving 60kW, 90kW, 304ps + water jet 1 units, 2 units	Gravel mix with cobble stone

(ps: Engine out put)

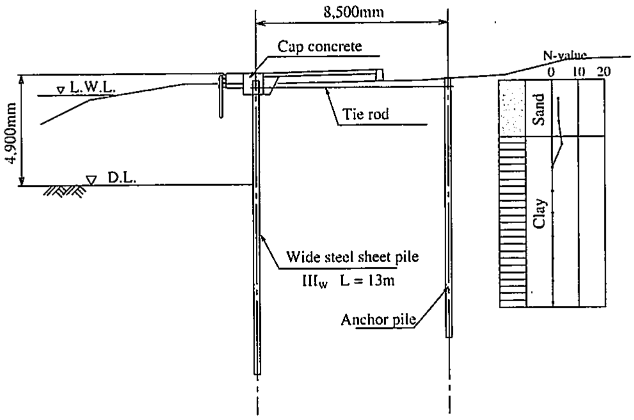


Fig. 15 Construction performance investigation test (No. 1) in actual project

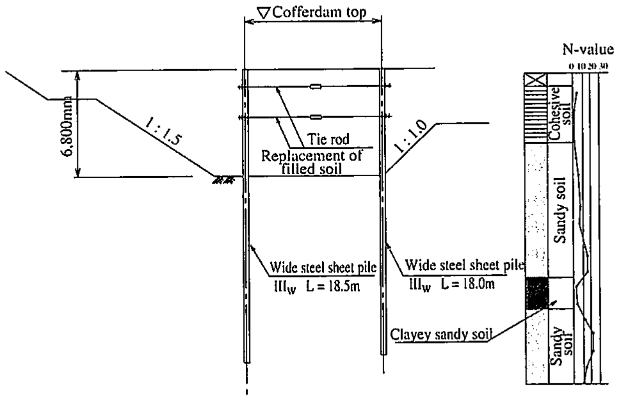


Fig. 16 Construction performance investigation test (No. 2) in actual project

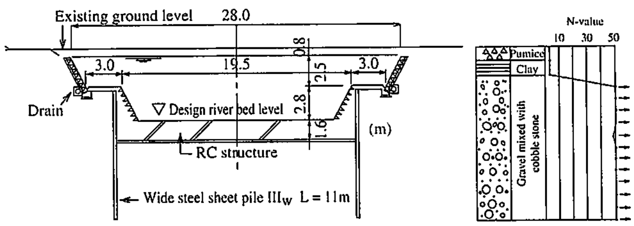


Fig. 17 Construction performance investigation test (No. 3) in actual project

Table 6 Results of tests in actual project (No.3)

Case	Site	Sheet pile	Vibratory hammer	Water jet	Driving time (min)
1	A	III_w	Electric, 60kW	1 unit	27.0
2	A	III_w	Electric, 90kW	1 unit	16.8
3	A	III_w	Electric, 60kW	2 units	18.0
4	A	III_w	Electric, 90kW	2 units	11.5
5	A	IV	Electric, 60kW	1 unit	21.7
6	A	III_w	Electric, 90kW	1 unit	14.2
7	B	III_w	Electric, 90kW	1 unit	23.0
8	B	III_w	Electric, 90kW	2 units	14.6
9	B	IV	Electric, 60kW	1 unit	17.7
10	B	III_w	Hydraulic, 304ps	1 unit	26.1
11	B	III_w	Hydraulic, 304ps	2 units	14.5
12	B	IV	Hydraulic, 304ps	2 units	15.1

large due to its large penetration resistance. Soundproofing measures (use of sound-insulating pipes, rulers, and pieces) were subsequently implemented to reduce the noise by 15.8 dB-A.

5.3.3 Evaluation

The vibratory hammer driving time per pile for the wide steel sheet piles was approximately the same as for conventional steel sheet piles. The wide steel sheet piles also produced good construction parameters such as high finished work quality, and noise and vibration. Hydraulic pressing were developed exclusively for the wide steel sheet piles and proved successful in installing the wide steel sheet piles.

6. Advantages of Wide Steel Sheet Piles

The wide steel sheet piles were compared with conventional steel sheet piles to highlight their economic advantages in terms of material and construction costs.

6.1 Material advantage

The steel weight per unit steel sheet pile wall area can be reduced 6 to 31% by using wide steel sheet piles (see **Fig. 18**). The greatest steel weight reduction of about 31% can be achieved if type II_w can be used in applications that have traditionally required the type III conventional steel sheet pile.

In actual design, self-standing steel sheet pile walls frequently installed in river projects differ in the depth of penetration into the ground with the section performance of the steel sheet piles used. **Fig. 19** shows the design conditions under which the wide steel sheet piles were compared with conventional steel sheet piles by focusing

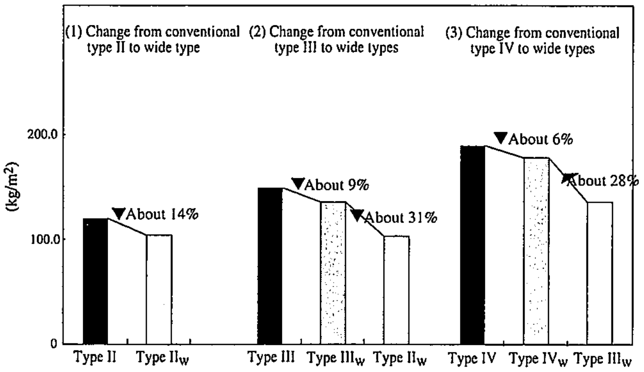


Fig. 18 Steel weight per unit steel sheet pile wall area

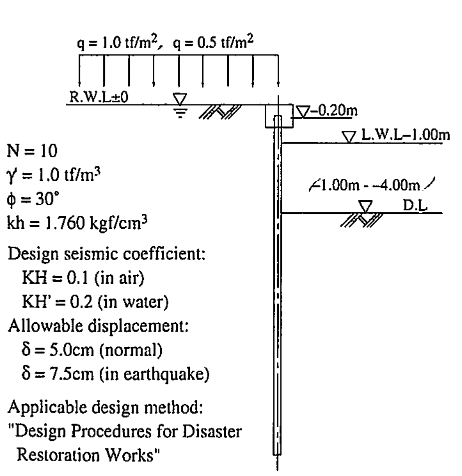


Fig. 19 Design conditions

on the steel weight per unit revetment extension that takes the difference in the penetration depth into account. The revetment was changed in the height H at 0.1-m intervals from 1 to 4 m and was designed with both the wide steel sheet piles and conventional steel sheet piles (see **Fig. 20**). The revetment can be built with type II and type II_w up to a height of 2.5 m, and the steel weight reduction per unit revetment extension is about 8%. When the revetment height exceeds 2.5 m, conventional steel sheet piles can be replaced by smaller types of wide steel sheet piles; for example, III→II_w, IV→III_w, and V_L→ IV_w. The steel weight reduction achieved by substitution of the wide steel sheet piles for conventional steel sheet piles is an average of about 21%.

6.2 Construction advantage

The Steel Sheet Pile Technical Committee of the Japanese Association for Steel Pipe Piles drafted estimation standards for the installation of the wide steel sheet piles by the vibratory hammer driving and hydraulic pressing methods before the establishment of estimation methods by concerned government agencies. The basic considerations are as follows:

1) The number of wide steel sheet piles to be installed per day should be the same as for conventional steel sheet piles.
2) When the driving depth is long or the soil is hard, a type one rank above that used for conventional steel sheet piles should be used for the wide steel sheet piles.

The advantage of reducing the construction cost by using the wide steel sheet piles depends on the difference between the "decrease (A) in the construction cost with the reduction in the number of piles installed" and the "increase (B) in the construction cost with the increase in the machine cost if there is a type upgrade". Since A is greater than B in all cases, the total construction cost can be reduced by using wide steel sheet piles. As one example, the driving cost per unit steel sheet pile wall area was calculated by assuming an N-value of 20 and the same lengths for both wide steel sheet piles and con-

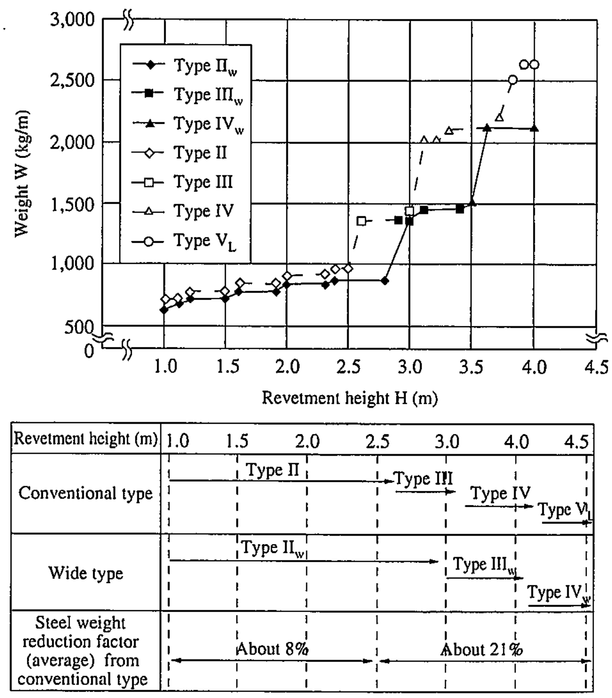


Fig. 20 Design of wide steel sheet piles as compared with conventional steel sheet piles

ventional steel sheet piles. The results for 8, 12, and 16 m long piles installed by the vibratory hammer driving and hydraulic pressing methods are shown in **Figs. 21 and 22**, respectively.

Use of wide steel sheet piles allows the driving cost to be reduced by 28 to 33% for the vibratory hammer driving method and by about 10% for the hydraulic pressing method, as compared with use of conventional steel sheet piles. The magnitude of the cost reduction differs between the vibratory hammer driving method and the hydraulic pressing method because the wide steel sheet piles allow existing models of vibratory hammers to be used, but require special models of hydraulic pressing.

As discussed above, wide steel sheet piles can reduce the construction cost in terms of both materials and construction.

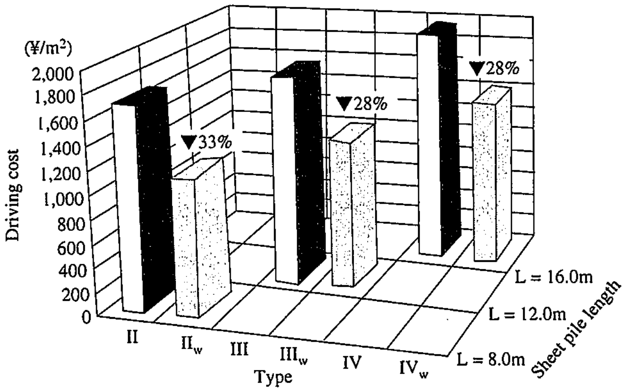


Fig. 21 Driving cost (vibratory hammer driving method) (N-value = 20)

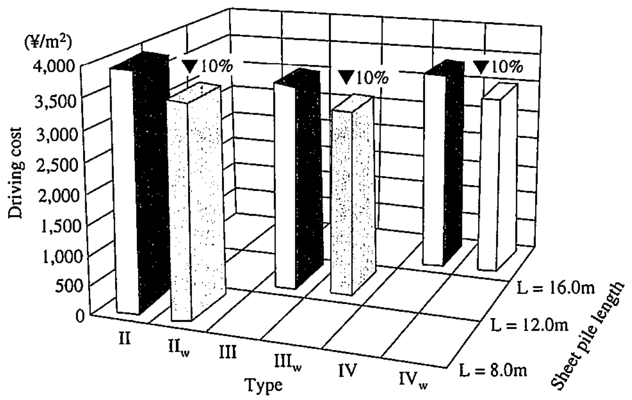


Fig. 22 Driving cost (hydraulic pressing method) (N-value = 20)

7. Conclusions

Wide steel sheet piles have found rapidly increasing usage since becoming available, partly because of the good timing with the government's resolve to reduce the construction cost of public works projects. The use of special machines for pressing the wide steel sheet piles has become widespread and they are readily available.

As future issues, we will have to establish a system for manufacturing heavy-duty corrosion-resistant coating for the wide steel sheet piles and verify whether or not longer lengths can be successfully installed. We hope that wide steel sheet piles will see ever increasing use.