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 Larsen 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 Larsen 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. C...
construction 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 selectivity using standard types (II to IV) and improved types (I to IV) 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 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.

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_c = 1 mm) in river applications (x_c = 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.

(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

<table>
<thead>
<tr>
<th>Type</th>
<th>Corrosion ratio $t_1/t_0$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wide</td>
<td>1.00 0.75 0.50 0.25 0</td>
</tr>
<tr>
<td>IIIw</td>
<td>81 83 86 88 90</td>
</tr>
<tr>
<td>IVw</td>
<td>85 87 89 90 92</td>
</tr>
<tr>
<td>Conventional</td>
<td>88 90 91 93 94</td>
</tr>
</tbody>
</table>

Table 2 Loading patterns in compression test

<table>
<thead>
<tr>
<th>Loading pattern</th>
<th>Compression part</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central axis compression</td>
<td><img src="image" alt="Central axis compression" /></td>
</tr>
<tr>
<td>Eccentric compression of web area</td>
<td><img src="image" alt="Eccentric compression of web area" /></td>
</tr>
<tr>
<td>Eccentric compression of flange area</td>
<td><img src="image" alt="Eccentric compression of flange area" /></td>
</tr>
</tbody>
</table>

Fig. 3 Schematic illustration of compression test

![Schematic Illustration](image)

(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 IIIw 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.
(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 IIIw) 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 (IL/L) 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 (IL). 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.

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 IIIw) and six conventional steel sheet piles (type III). The wide steel sheet piles and the conventional steel sheet 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 \( \mu \)m, the analysis was conducted in the load region where the strains observed in the test steel sheet piles was 300 \( \mu \)m 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.
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 con-
ventional 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 IIIe in the sandy soil of the No. 1 test and was approximately the same for both type IIIe and type III in the cohesive soil of the No. 2 test. The current value was about 15% and 25% greater for type IIIe in the Nos. 1 and 2 tests, respectively. In the No. 5 test, the type IIIe was driven by a special pressing machine which was confirmed to have satisfactory construction performance. A type IIIe 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 dBA (45 kW) and 75.4 dBA (60 kW), and the vibration at the same distance was 74.5 dB.

Table 4 Preliminary validation tests

<table>
<thead>
<tr>
<th>No.</th>
<th>Steel sheet pile data</th>
<th>Construction method and machine</th>
<th>Ground condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>IIIe</td>
<td>15 m, 14 m</td>
<td>Vibriatory hammer driving</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15 m, 14 m</td>
<td>Sandy soil</td>
</tr>
<tr>
<td>2</td>
<td>IIIe</td>
<td>15 m, 14 m</td>
<td>Vibriatory hammer driving</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15 m, 14 m</td>
<td>Cohesive soil</td>
</tr>
<tr>
<td>3</td>
<td>IIIe</td>
<td>15 m, 14 m</td>
<td>Vibriatory hammer driving</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15 m, 14 m</td>
<td>Alternate strata of sandy and cohesive soil</td>
</tr>
<tr>
<td>4</td>
<td>IIIe</td>
<td>10 m, 9 m</td>
<td>Vibriatory hammer driving</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10 m, 9 m</td>
<td>Gravel and cohesive soil</td>
</tr>
<tr>
<td>5</td>
<td>IIIe</td>
<td>15 m, 14.5 m</td>
<td>Hydradric pressing</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15 m, 14.5 m</td>
<td>Alternate strata of sandy and cohesive soil</td>
</tr>
</tbody>
</table>

![Fig. 12 Preliminary validation test (No. 1)](image)

![Fig. 13 Preliminary validation test (No. 2)](image)

![Fig. 14 Preliminary validation test (No. 5)](image)

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 IIIw 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 IIIw than type IV and was 5 to 17% shorter at point B for type IIIw 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 IIIw was practically the same as type IV in vibration. Type IIIw 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)](image)

Table 5 Construction performance investigation tests in actual projects

<table>
<thead>
<tr>
<th>No</th>
<th>Steel sheet pile data</th>
<th>Construction method and machine</th>
<th>Ground condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>IIIw 13m 12m</td>
<td>Vibratory hammer driving 45kW, 60kW</td>
<td>Cohesive soil</td>
</tr>
<tr>
<td>2</td>
<td>IIIw 18.5m 13.5m</td>
<td>Vibratory hammer driving 60kW</td>
<td>Sandy soil</td>
</tr>
<tr>
<td>3</td>
<td>IIIw 14m IV 14m</td>
<td>Vibratory hammer driving 60kW, 90kW, 304ps + water jet 1 units, 2 units</td>
<td>Gravel mix with cobble stone</td>
</tr>
</tbody>
</table>

(ps: Engine output)

![Fig. 15 Construction performance investigation test (No. 1) in actual project](image)

![Fig. 16 Construction performance investigation test (No. 2) in actual project](image)

![Fig. 17 Construction performance investigation test (No. 3) in actual project](image)

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

<table>
<thead>
<tr>
<th>Case</th>
<th>Site</th>
<th>Sheet pile</th>
<th>Vibratory hammer</th>
<th>Water jet</th>
<th>Driving time (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>A</td>
<td>IIIw</td>
<td>Electric, 60kW</td>
<td>1 unit</td>
<td>27.0</td>
</tr>
<tr>
<td>2</td>
<td>A</td>
<td>IIIw</td>
<td>Electric, 90kW</td>
<td>1 unit</td>
<td>16.8</td>
</tr>
<tr>
<td>3</td>
<td>A</td>
<td>IIIw</td>
<td>Electric, 60kW</td>
<td>2 units</td>
<td>18.0</td>
</tr>
<tr>
<td>4</td>
<td>A</td>
<td>IIIw</td>
<td>Electric, 90kW</td>
<td>2 units</td>
<td>11.5</td>
</tr>
<tr>
<td>5</td>
<td>A</td>
<td>IV</td>
<td>Electric, 60kW</td>
<td>1 unit</td>
<td>21.7</td>
</tr>
<tr>
<td>6</td>
<td>A</td>
<td>IIIw</td>
<td>Electric, 90kW</td>
<td>1 unit</td>
<td>14.2</td>
</tr>
<tr>
<td>7</td>
<td>B</td>
<td>IIIw</td>
<td>Electric, 90kW</td>
<td>2 units</td>
<td>23.0</td>
</tr>
<tr>
<td>8</td>
<td>B</td>
<td>IIIw</td>
<td>Electric, 90kW</td>
<td>2 units</td>
<td>14.6</td>
</tr>
<tr>
<td>9</td>
<td>B</td>
<td>IV</td>
<td>Electric, 60kW</td>
<td>1 unit</td>
<td>17.7</td>
</tr>
<tr>
<td>10</td>
<td>B</td>
<td>IIIw</td>
<td>Hydraulic, 304ps 1 unit</td>
<td>26.1</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>B</td>
<td>IIIw</td>
<td>Hydraulic, 304ps  2 units</td>
<td>14.5</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>B</td>
<td>IV</td>
<td>Hydraulic, 304ps  2 units</td>
<td>15.1</td>
<td></td>
</tr>
</tbody>
</table>
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, 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 IIw 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 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 IIw 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 → IIw, IV → IIIw, and V → IVw. 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 an 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. 18 Steel weight per unit steel sheet pile wall area](image-url)

![Fig. 19 Design conditions](image-url)

![Fig. 20 Design of wide steel sheet piles as compared with conventional steel sheet piles](image-url)
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.