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# Static Behavior of Double Sheet-Pile Wall Structures with High Rigidity Partitions*


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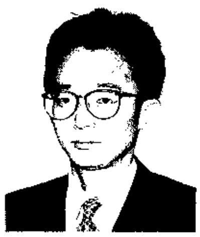

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## 1 Introduction

Double sheet-pile wall structures are structure created by filling sand between sheet-piles or steel pipe sheet-piles driven in two rows. Because of features such as excellent workability, large loading capacity and good cut-off ability, double sheet-pile wall structures are used in cofferdams for the dry work in harbors and rivers and such permanent works as bulkheads, quaywalls and breakwaters.

Kawasaki Steel and the Ministry of Transport have since the 1970s conducted continuous research on the behavior of double sheet-pile wall structures. On the basis of these research projects, Sawaguchi's method (1974)[1] and Ohori et al's method (1984)[2] were proposed. Under these methods, behavior is analyzed by regarding double sheet-pile wall structures as composite structures of sheet-piles, sand fill and the ground. These methods have been used in design and analysis.

Under the methods that prevailed before these analytical methods, the equilibrium of the limit state between the shear resistance of the sand fill and the sliding resistance of the whole double sheet-pile wall structure was examined[3]. These new methods have made it possible to evaluate the behavior of double sheet-pile wall structures composed of sheet-piles and sand fill, which have high flexibility, in a form close to the actual condition.

In recent waterfront development and similar project, work involving soft ground and deep water conditions has increased, and high loading capacity and control of deformation have been required of double sheet-pile wall structures. The authors are conducting research on high-rigidity double walls in order to meet these requirements.

This paper describes the concept of high-rigidity double sheet-pile wall structures and reports the static behavior of these structures so far verified in model tests.

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## 2 Concept of Double Sheet-Pile Wall Structures with High Rigidity Partitions

### 2.1 Conventional Measures to Increase Rigidity

The following methods are generally adopted to increase the loading capacity of double sheet-pile wall structures and to reduce deformation:

(1) Increase in the wall breadth of double sheet-pile wall structure

(2) Increase in the flexural rigidity of sheet-pile

(3) Stabilization of soft ground

(4) Increase in the strength of filling materials (use of gravel)

Furthermore, the following reinforcing methods are available in combination with other processes:

(5) Construction of an RC slab at the top of the double sheet-pille wall[4]

(6) Steel pipe sheet-pile well (king post type of bulkhead of solid waste landfill site outside the Tokyo Bay Central Breakwater)

(7) Combined application of struts[5] and combined application of earth-anchors[6]

(8) Use of multi-stage tie rods[7, 8]

Although the effects of the above methods (1) to (4) have been clarified considerably by studies to date, there are limits to an increase in the loading capacity due to restrictions in materials and execution of work, and these methods may sometimes be uneconomical. For some of the reinforcement measures combined with other processes (5) to (8), there are problems in workability and economical efficiency, and the behavior of double sheet-pile wall structures is not always clear.

### 2.2 Proposal of New Double Sheet-Pile Wall Structures with High Rigidity Partitions

As mentioned above, the important points for an increase in the loading capacity of double sheet-pile wall structures are how to increase the strength of the sand-fill portion and how to interlink the front and rear sheet-piles in two rows, in addition to how to increase the strength of the ground and the flexural rigidity of the sheet-piles. This means an increase in the rigidity of the whole structure by enhancing the integrity of the double sheet-pile wall structure, which is a composite structure of sheet-piles in two rows and sand fill.

High-rigidity double sheet-pile wall structures with steel members in the sand-fill portion as shown in **Figs. 1** and **2** were developed in consideration of workability, economical efficiency, etc. Figure 1 shows the truss partition type, in which steel trusses are used from the top end of the sand-fill portion to a certain depth. This type combines the effect of fixing the top of the double wall and the effect of reinforcing the sand fill. Figure 2 shows the panel partition type, in which panels are used as partition walls to the deep part of the sand fill. This type is installed to the deep part of ground as required. In this latter type, the integrity of the whole double sheet-pile wall structure is high compared with the former type, and a decrease in deformation can be expected.

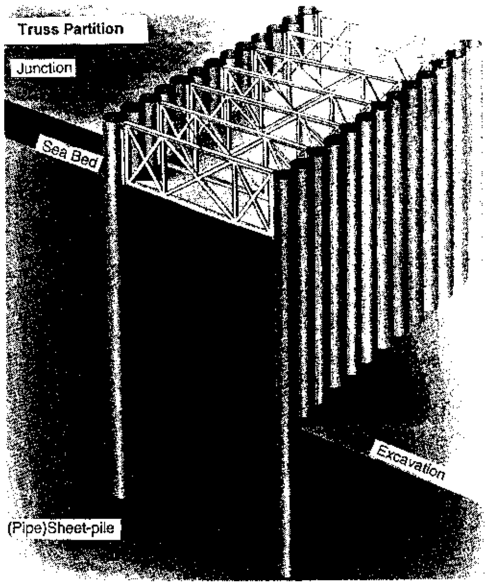


Fig. 1 High rigidity double wall (truss partition type)

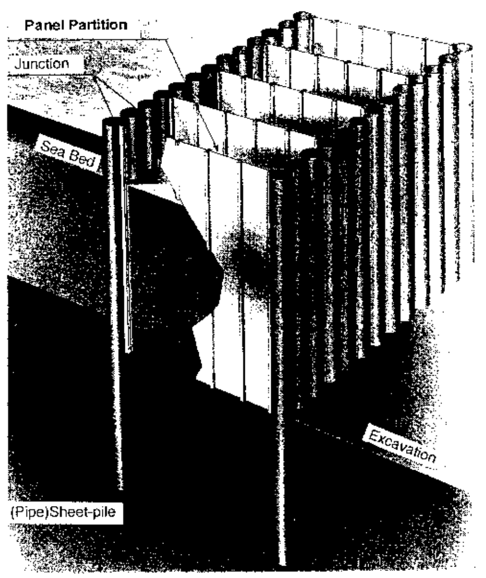


Fig. 2 High rigidity double wall (panel partition type)

## 3 Purpose and Method of Model Tests

### 3.1 Purpose

Static tests using models were conducted on new type high-rigidity double sheet-pile wall structures to investigate how the loading capacity and deformation differ depending on the high rigidity of the partitions or the

Table 1 Test cases (cofferdam type, front ground excavation test)

| | Case[a] | Type | | Initial cofiguration | | Excavation (cm) | Wall breadth (cm) |
|---|---|---|---|---|---|---|---|
| | | | | Wall height (cm) | Embedment depth (cm) | | |
| High rigidity double wall with partition | X-1, X-2 | Panel partition | | 24 | 127 | 47 | 50 |
| | Z-1, Z-2 | Truss partition | | | | | |
| | J-1, J-2 | Shear slip panel partition | | | | | |
| Conventional double wall | K-1 | No partition | Narrow breadth | 24 | 127 | 47 | 25 |
| | Y-1, Y-2 | | Medium breadth | | | | 50 |
| | L-1 | | Wide breadth | | | | 100 |
| Rigid body like a caisson | F-1 | Rigid body with leg-wall model | | 24 | 127 (leg : 80 cm) | 47 | 50 |
| | G-1 | Rigid body model | | | 127 | | |
| | H-1 | Shallow rigid body model | | | 47 | | |

[a]Suffixes of case ID of 1 and 2 denote the test conditions that water pressure acts on the front and rear wall, respectively.

Table 2 Test cases (quaywall type, lateral loading test using hydraulic jack system)

| | Case[a] | Partition type | Wall height (cm) | Embedment depth (cm) | Wall breadth (cm) |
|---|---|---|---|---|---|
| High rigidity double wall with partition | JA1, JA2 | Truss partition | 71 | 80 | 50 |
| | JB1, JB2 | Panel partition | | | |
| | JC1, JC2 | Shear slip panel partition | | | |
| Conventional double wall | JD1, JD2 | No partition | 71 | 80 | 50 |

[a]Suffixes of case ID of 1 and 2 denote the distributed loading case with three jacks and top loading case with one jack, respectively.

degree of connection of the sheet piles proper in two rows and to establish design techniques.

In usual double sheet-pile wall structures also, partitions (partitions using sheet-piles) are often used for reasons of execution of work because the partitions are installed in the sand-fill portion. However, the extent of the effect of the partitions on the behavior of the whole structure has not been clarified. Therefore, it was decided to examine not only truss partitions and panel partitions, but also the use of such materials as sheet-piles, in which shear slide of joints occurs, as partitions.

## 3.2 Methods of Tests

### 3.2.1 Cases of model test

In the tests, two test methods, the cofferdam type and the reclaimed bulkhead type, were adopted in consideration of how double sheet-pile wall structures are used. In the cofferdam type, the drainage and excavation of the front ground of the double sheet-pile wall are conducted after the construction of the double wall. In the reclaimed bulkhead type, backfilling is conducted after the construction of the double wall.

Five types of structural models were adopted. They are the three kinds of partition-type models of panel partition, truss partition and shear slip panel partition, a model without a partition, and a model of a perfect rigid body. This test cases are shown in **Tables 1** and **2**. The truss partition is 24 cm deep from the sheet-pile head to the sea bed. The panel partition and shear slip panel partition are 71 cm deep to the designated level of excavation. All types of partitions are arranged at intervals of 30 cm along an alignment from front to back.

### 3.2.2 Method of model tests

The model tests were conducted using models on a scale of about 1/25 of an actual double wall. An example of a test of the cofferdam type is shown in **Fig. 3**; a test of the bulkhead type is shown in **Fig. 4**.

Most of the previous studies were carried out on double sheet-pile wall structures of the bulkhead type, in which the earth pressure from the rear side is dominant. However, a recent study showed a difference in behavior in front-wall loading and rear-wall loading.[9] In double sheet-pile wall cofferdams, the water pressure is dominant over the earth pressure, and the share of earth and water pressures between the front and rear walls differ depending on the soil condition at the site, the concept of the cut-off wall, etc. In the present tests, the effect of the partitions of a double sheet-pile wall was examined by comparing two ideal cases where the whole water pressure is applied to only the front or rear walls.

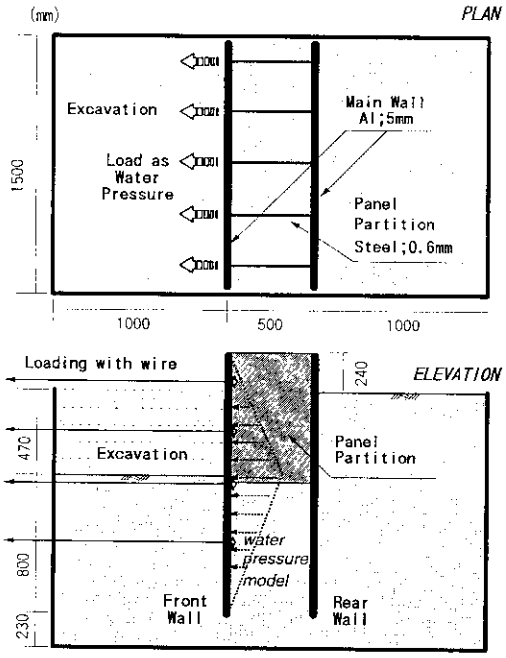


Fig. 3 Excavating test apparatus (case X-1)

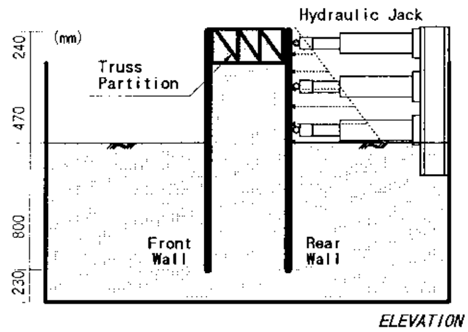


Fig. 4 Loading test apparatus (case JA1)

In consideration of simplicity and reproducibility, dry sand was used in the tests. Water pressure distribution was presumed in such a manner that the hydrostatic pressure due to the difference of water head becomes zero at the bottom of the wall and the water pressure was distributed and applied to wires installed in multiple stages in the direction of depth. A water pressue corresponding to the given drawdown of water level on the front ground of a double wall was applied, and the front ground is then excavated. The tests were conducted by repeating this procedure.

In the tests of the bulkhead type, pressure was gradually applied using a hydraulic jack system from the rear side in two cases, one of top loading based on an image of mooring force, wave force, etc. and another where pressure is applied by simulating the distributed pressure using jacks installed in three stages in the direction of depth based on an image of the earth pressure of backfill. For the three-stage pressures, the loading points and load ratio of the respective jacks were set for the earth pressure above the ground level in consideration of lateral load and the overturning moment at ground level.

Kashima silica sand #6 was used in the tests. As the structural models, 5 mm thick aluminum plates were used in the models of sheet-piles and trusses and 0.6 mm thick galvanized sheets were used in the panel partitions and shear slip panel partitions. The rigid body models were box-shape models fabricated by welding and assembling 3.2 mm thick steel plates.

The model walls were built by temporarily fixing the wall model in a predetermined position beforehand and then spreading sand while controlling the thickness of the stratum in 10 cm steps. After the completion of the ground, the temporary fixing of the model wall was undone and filling-sand was filled to the top of the sheet-pile as required.

## 4 Characteristics of Displacement Behavior

### 4.1 Results of Cofferdam Type Test (Front Excavation Type)

**Figures 5** and **6** show the relationship between the

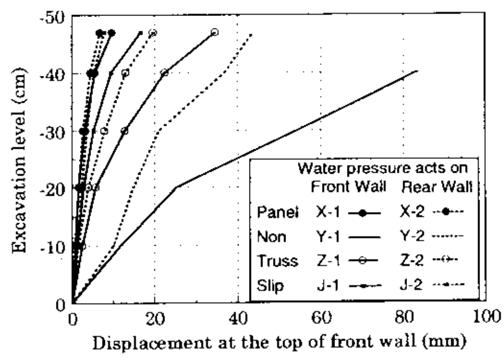


Fig. 5 Displacement curve (comparison of partition types)

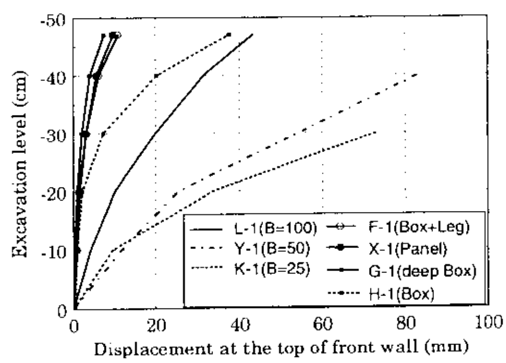


Fig. 6 Displacement curve (comparison of both wall breadth and rigidity as a wall box)

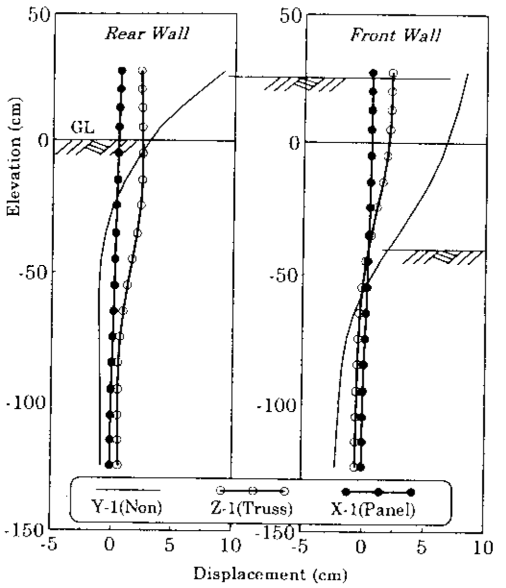


Fig. 7 Deformation of the wall (typical cases)

front excavation level and the lateral displacement at the top of the front wall (the value is zero when sand fill is completed) in representative cases. The displacement distribution calculated from the bending moment is shown for reference in **Fig. 7**.

#### 4.1.1 Difference in displacement behavior due to difference in sheet-piles to which water pressure is applied

In all structural types, the lateral displacement at the top of the front wall is larger when water pressure is applied to the front wall. This tendency is especially great in cases Y1 and Y2 of the no-partition type.

The reason for this might be thought to be as follows. When water pressure is applied to the front wall, the sand-fill portion including the embedment is brought into the tension state and its rigidity decreases, with the result that the effect of transmitting the force from the rear wall to the deep part of the front wall decreases and the reaction force of the rear wall also diminishes.

When there is no partition, the load transmission between the front and rear walls is conducted only through the tie rods at the head. The rear wall shows large displacement in the same manner as a projecting pile due to the softening of the sand-fill and can share only a small load. Conversely, when the walls are provided with partitions, the partitions transmit the tensile force directly to the rear wall and, therefore, load sharing is good.

Furthermore, because the partitions of the sand-fill portion transmit a large shearing force, the flexural rigidity as an H-shaped section composed of sheet-piles in two rows and partitions is displayed, and deformation is governed by the flexural rigidity of the whole wall. As a result, the difference in sheet-piles which allows the action of pressure seems to decrease.

#### 4.1.2 Difference in displacement behavior due to difference in type of structure

(1) Effect of Rigidity of Partitions

The displacement at the top changes depending on the rigidity of the partitions. That is to say, in the present tests the rigidity of the partitions increases in the order: no partition (Y), shear slip panel partition (J), panel partition (X), and rigid body (H), and the displacement at the top decreases accordingly.

(2) Effect of Depth of Partitions

The displacement is larger when truss partitions are used at the top (Z) than with shear slip panel partition (J).

The reason why the effect of depth is greater than that of the rigidity of the partitions may be that in these tests water pressure was applied even to the embedment in order to cause deformation in deep portions. In this connection, it might be pointed out that the displacement is smaller when truss type partitions constraining the head are used in top loading from the rear side, as will be described later.

(3) Effect of Displacement Deformation of Partitions

In the tests in which water pressure is applied to the rear wall, the difference in displacement between the panel partition (X2) and shear slip panel partition (J2) is small.

In this case, it might be thought that the shear deformation mode is not very strong, with the result that the effect of the shear slip in joints did not appear.

(4) Effect of Rigidity of Sand-Fill Portion

There is scarcely any difference in displacement between the case where the lower part of the rigid body is provided with wall-like piles (F1) and the panel partition (X1).

From the foregoing, it might be thought that the part where high-rigidity partitions necessary for the transmission of force are installed shows almost the same behavior as that of a rigid body.

The results of a comparison of the cases where no partition is installed and the wall breadth is changed (K1, Y1 and L1) show that displacement decreases with increasing wall breadth.

It is interesting that the installation of partitions and an increase in the wall breadth have the same effect on displacement behavior.

In conventional design, the shear resistance moment of the sand-fill portion is expressed by the function of wall breadth $B$. Likewise, under Ohori et al's method, the shearing force of sand-fill portion is represented by the relation to wall breadth $B$, as in $\tau = BG\theta$ ($G$ is the shearing modulus and $\theta$ is the angle of shear deformation). It might be thought that this suggests a method of evaluating partitions.

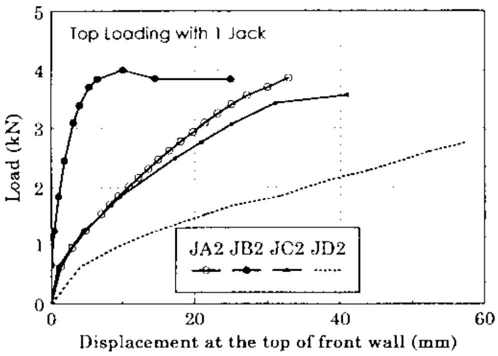


Fig. 8 Displacement curve (1-jack top loading tests)

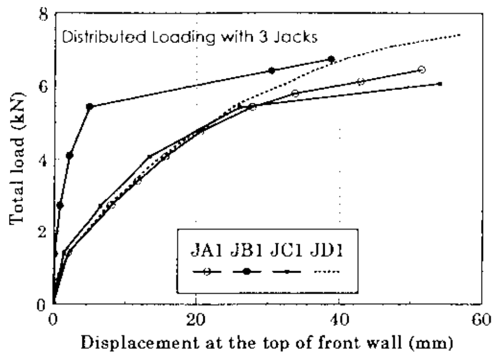


Fig. 9 Displacement curve (3-jack loading tests)

## 4.2 Results of Bulkhead Type Test (Rear Loading)

For the loading tests from the rear side using a jack system, the relationship between the load of each case (total load) and the lateral displacement at the top of the front wall is shown in **Fig. 8** (top loading) and **Fig. 9** (distributed loading).

### 4.2.1 Case of top loading

In the case of top loading, there is a clear tendency toward decreasing displacement at the top of the front wall in proportion to the rigidity of the partitions. Although there is no great difference in the maximum load in the test cases except with the no-partition type (JD2), displacement is clearly different and the initial rigidity also differs greatly.

In the panel partition type (JB2), different tendencies are observed in the behavior after maximum load at a displacement of about 10 mm.

Because light-gauge sheets were used in the models of the panel partition, the out-of-plane bending rigidity of the models is considerably smaller than shearing rigidity. For this reason, it might be thought that buckling of the partitions due to compression occurs after a maximum load is reached. It seems that this is also affected by the fact that the sand-fill is loose and has small constraints on the out-of-plane deformation of the partitions.

### 4.2.2 Case of distributed loading

In the panel partition type (JB1), the initial rigidity is very high. However, the respective cases show no great difference in the maximum load, and the effect of the increased rigidity of partitions is not reflected. The load in the no-partition type (JD1) is larger than with top loading.

Top loading provides a load system in which the overturning moment dominates over lateral force, while sliding tends to become the dominant mode in distributed loading; it might be thought that this is one of the reasons for the above phenomenon. When deformation occurs in the sliding mode, the front wall, sand-fill portion and rear wall make translational lateral movements if the sand-fill portion transmits compressive force; for this reason, there is no great difference except for the elastic deformation of the sand-fill portion.

Conversely, it might be thought that in rigid partitions compressive force is transmitted directly to the front wall, whereas force is dispersed to the deeper part of the front wall when the sand-fill is only sand (without a partition).

It seems that the deformation mode changes depending on the balance among the wall breadth, wall height, load system and reaction force distribution. It is interesting that these factors produce a difference in the effect of partitions; this is an item for further studies.

## 5 Bending Moment

The bending stress of sheet-pile walls, along with displacement, is an important evaluation item of design. The condition of the maximum bending moment occurring in the front and rear walls is shown here. The bending moment is indicated by the increase and decrease caused by excavation if it is taken as zero upon completion of the sand-fill. In some cases, the point at which the extracted maximum moment occurs shifts from the upper part of the wall to the embedment because the maximum moment was evaluated by an absolute value.

Furthermore, it should be noted that as shown in **Fig. 10**, the bending moment distribution of the front wall is different from that of the rear wall.

## 5.1 Results of Cofferdam Type Test (Front Excavation Type)

The relationship between the excavation level on the front ground of the double wall and the maximum bending moment is shown in **Fig. 11**.

In a group of cases where water pressure is applied to the front wall (X1, Y1, Z1 and J1), both the front and rear sheet-pile walls show small maximum moments in the panel partition type (X1) and shear slip panel partition type (J1) and high values in the truss partition type

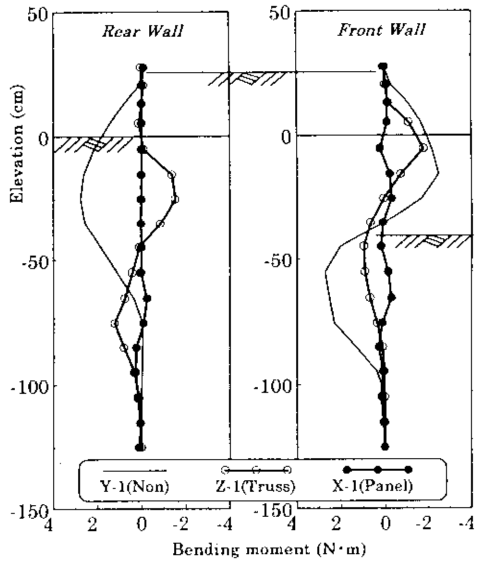


Fig. 10 Moment distribution (typical cases of excavation tests)

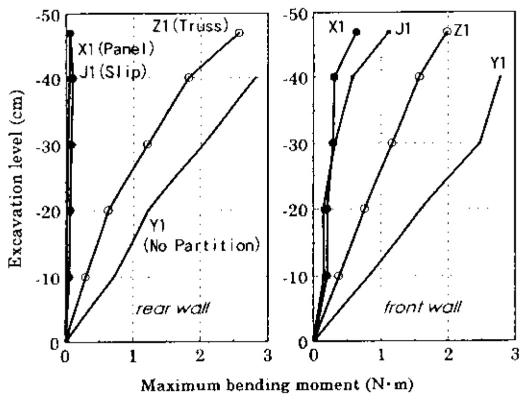


Fig. 11 Maximum moment curve (excavation tests)

(Z1) and no-partition type (Y1), as in the displacement behavior at the top of front wall.

Furthermore, a very small moment of the rear wall is a characteristic of the panel partition type and shear slip panel partition type. Because sheet-like partitions are installed, the sand-fill portion, including the parts deeper than the bottom ends of the partitions, behaves like a rigid body, with the result that bending may be less apt to occur in the rear wall.

When water pressure was applied to the rear wall, the dependence of the magnitude of generated moments upon structural types was almost the same as with front loading (data are omitted). However, the generated moments were characteristically small as a whole.

### 5.2 Results of Bulkhead Type Test (Rear Distributed Loading)

The relationship between the load applied from the rear side and the maximum bending moment is shown in **Fig. 12**.

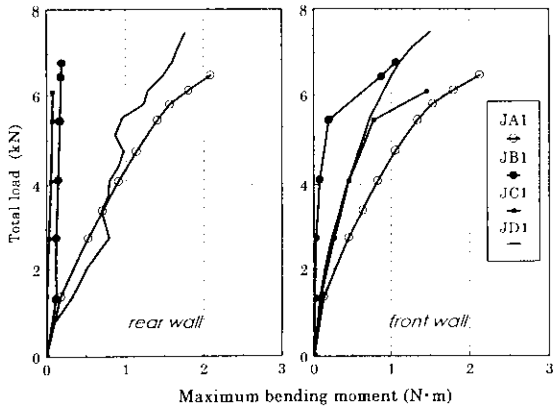


Fig. 12 Maximum moment curve (3-jacks loading tests)

As with the excavation type tests, the maximum moment is small in the panel partition type (JB) and shear slip panel type (JC) and large in the truss partition type (JA) and no-partition type (JD).

As a characteristic of the shear slip panel type, the moment of the rear wall is smaller than that of the front wall.

The panel partition type is characterized by the phenomenon that, as with the displacement behavior at the top of the front wall, the bending moment of only the front wall increases after peak load. This phenomenon may be accounted for by the assumption that the deep part of the partition buckles and no longer transmits load and the bending of the front wall proceeds by the transmission of load by the head only.

## 6 Conclusion

Measures to cope with deep water and soft ground are in urgently needed in the projects. The authors adopted, as one means of meeting this request, new structures called the double sheet-pile wall structures with high-rigidity partitions, embodying a new concept in the form of partitions while taking full advantage of the features of the conventional process of double sheet-pile wall.

Through an investigation of behavior by model tests, the authors demonstrated in this paper that double sheet-pile wall structures with high-rigidity partitions have a rational deformation characteristic.

To summarize the results of the model tests, the conventional double sheet-pile wall structures and the high-rigidity double sheet-pile wall structures proposed by the authors have the following behavior:

(1) The behavior of double sheet-pile wall structures have different resistance mechanisms depending on how external forces work, causing great differences in their loading capacity and deformation. In particular, conventional double sheet-pile wall structures without a partition can display, only small resistance when the front wall is subjected to dominant loads.

(2) In double sheet-pile wall structures, it is important for the sand-fill portion to have sufficient resistance to compression, tension and shearing. The loading capacity and rigidity are increased by installing partitions in the sand-fill portion.
(3) In a load system with a dominant overturning moment, the shearing force of the sand-fill portion is large and the shearing rigidity of the partitions is important. When the sliding mode dominates, however, the transmission of tensile and compressive forces is a key point, and even partitions such as sheet-piles, where shear slide occurs, are effective.
(4) Not only a reduction in displacement, but also a decrease in the bending stress of sheet-piles can be expected from the installation of partitions in the sand-fill portion.

In the model tests, detailed data on earth pressure and shear strain, including the test cases described in this paper, were gathered. The authors are presently examining resistance mechanisms, deformation models, numerical analysis, etc.

Structural analysis of partition members and loading tests of partition joints that are important for the construction of actual structures have been carried out separately, and the examination of joint structures capable of withstanding the tensile force and shearing force working on partitions has been completed. The authors intend to report these results at other opportunities.

Lastly, the authors would like to mention that this study was carried out as the joint research project by the Port and Harbor Research Institute of the Ministry of Transport and Kawasaki Steel. Furthermore, the authors would like to thank the persons concerned of the Second District Bureau of Port Construction of the Ministry of Transport for their helpful advice in carrying out this study.

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