Development of Sheet-Pile Foundation that Combines Footing with Sheet Piles

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The authors propose sheet-pile foundation as a new viable foundation structure. The construction costs of this type of foundation are lower than those for pile foundation, and it can be used more widely than shallow foundation. In this research, a series of laboratory static loading tests and full-scale field tests were carried out to evaluate the fundamental characteristics of sheet-pile foundation. The tests showed that its horizontal resistance is larger than that of shallow foundation, and that it exhibits excellent performance against seismic forces.

Keywords: sheet-pile foundation, shallow foundation, horizontal loading, seismic design

1. Introduction

There has recently been an increase in the amount of construction work in densely populated urban areas of Japan. In order to ease traffic congestion, for example, railroads running through urban areas are being relaid on elevated bridges, which are built close to existing structures. Usually, the space available for construction work in urban areas is very limited, and such work requires the minimization of costs, noise and vibration. The disposal of surplus soil generated from construction work must also be taken into consideration.

To alleviate the above problems, sheet-pile foundation that combines footing and sheet piles is proposed as a new type of foundation [1, 2]. Since this kind of foundation reinforces the ground with sheet piles, the bearing capacity and horizontal seismic resistance are higher than those of shallow foundation. Its applicability is wider than that of shallow foundation, and it can be used, for example, on the loose sandy ground for which pile foundation has conventionally been used. The construction costs are almost the same as those of shallow foundation, and are lower than those of pile foundation. On the other hand, since pile excavation is not necessary, the technique avoids the various problems of pile foundation such as noise, vibration and the disposal of surplus soil. Figure 1 shows an outline of sheet-pile foundation compared with spread foundation.

In this research, a series of laboratory static loading tests and full-scale field tests were carried out to evaluate the performance of sheet-pile foundation.

2. Laboratory model tests

2.1 Outline of modeled ground and foundations

Model ground was made using dry Toyoura sand in a sand container, constituting a two-dimensional model in plane strain condition. The container’s front and back

![Fig. 1 Outline of sheet-pile foundation](image-url)
surfaces were made of transparent acrylic to allow observation of the ground deformation. In order to reduce friction between the acrylic plate and the sand, rubber membranes treated with grease were pasted on the acrylic. Target points were also marked on the rubber membrane, and their displacement was measured using an image processing system to process photographs taken with a digital camera through the acrylic plate [3]. Table 1 summarizes the conditions of the modeled ground. The relative density \( D_r \) of the modeled ground was set at 90% or 60%, and was controlled by the height of the sand hopper.

The model’s footing was represented by an aluminum block of 100 mm in width (\( B \)) placed on the modeled ground’s surface. The model sheet pile was made using phosphor bronze plates of 0.2 mm in thickness, which were pressed into the concavo-convex form shown in Fig. 2. Length \( L \), by which the modeled sheet pile was pushed into the sand, was 100 mm (\( L/B = 1.0 \)) or 50 mm (\( L/B = 0.5 \)). The value of \( \beta L \) (shown in Equation (1)) of the modeled sheet piles was the same grade as that of the prototype.

\[
\beta L = \frac{4k_h D}{AEI} \cdot L \tag{1}
\]

where \( \beta \) : characteristic value of pile (1/m), \( k_h \) : coefficient of horizontal subgrade reaction (kN/m\(^3\)), \( D \) : width of sheet piles (m), \( EI \) : flexural rigidity of sheet pile (kNm\(^2\)), \( L \) : length of sheet pile (m). Table 2 summarizes the specifications of the modeled sheet piles. In addition, the sheet-pile model was buried in the model ground.

### 2.2 Horizontal static reciprocal loading tests

Since earthquake resistance evaluation is very important in the design of foundation structures in Japan, horizontal loading tests were conducted to simulate the inertia force of an earthquake. This force was modeled by applying horizontal loads at the position corresponding to the bridge pier top.

An outline of the tests is shown in Fig. 3. The horizontal displacement was applied with a screw jack statically and reciprocally at a point 230 mm from the footing model bottom corresponding to the bridge pier top. An air cylinder was used to keep the vertical load at 1.2 kN, which was about 10% of the bearing capacity of the shallow foundation for \( D_r = 90\% \). Tests were carried out for the four cases shown in Table 3 (two for shallow foundation without sheet piles and the other two for sheet-pile foundation).

### Table 1 Conditions of modeled ground

<table>
<thead>
<tr>
<th>Ground size ((W \times H \times D))</th>
<th>2000 mm (\times) 580 mm (\times) 600 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground material</td>
<td>Dry Toyoura sand</td>
</tr>
<tr>
<td>Dry unit weight ( \gamma_d )</td>
<td>( \gamma_d = 16.2 \text{kN/m}^3 ) (( D_r = 90% ))  ( \gamma_d = 15.1 \text{kN/m}^3 ) (( D_r = 60% ))</td>
</tr>
<tr>
<td>Lubricated layer</td>
<td>Rubber membrane (( t = 0.2 \text{mm} )) with grease (10 ( \mu \text{m} ))</td>
</tr>
</tbody>
</table>

### Table 2 Specifications of modeled sheet piles

<table>
<thead>
<tr>
<th></th>
<th>Prototype TYPE IV</th>
<th>Modeled sheet-pile</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness</td>
<td>15.5 mm</td>
<td>0.2 mm</td>
</tr>
<tr>
<td>Height of concavo-convex form</td>
<td>340 mm</td>
<td>1.5 mm</td>
</tr>
<tr>
<td>Width of footing ( B )</td>
<td>4.8 m</td>
<td>100 mm</td>
</tr>
<tr>
<td>Width of sheet piles ( D )</td>
<td>4.8 m</td>
<td>596 mm</td>
</tr>
<tr>
<td>Young’s modulus ( E )</td>
<td>200 kN/mm(^2) (steel)</td>
<td>110 kN/mm(^2) (phosphor bronze)</td>
</tr>
<tr>
<td>Geometrical moment of inertia ( I )</td>
<td>1.28 ( \times ) 10(^4) ( \text{m}^4 )</td>
<td>42.9 ( \text{m}^4 )</td>
</tr>
<tr>
<td>Coefficient of horizontal subgrade reaction ( k_h )</td>
<td>78,600 kN/m(^2) (sand N = 30)</td>
<td>45,700 kN/m(^2) (( D_r = 90% ))</td>
</tr>
<tr>
<td>Length ( L )</td>
<td>4.8 m (( L/B = 1.0 ))  2.4 m (( L/B = 0.5 ))  100 mm (( L/B = 1.0 ))  50 mm (( L/B = 0.5 ))</td>
<td>( \beta L )</td>
</tr>
</tbody>
</table>

### Table 3 Cases of horizontal loading tests

<table>
<thead>
<tr>
<th>Case</th>
<th>Density of ground</th>
<th>Foundation form</th>
</tr>
</thead>
<tbody>
<tr>
<td>HD1</td>
<td>( D_r = 90% ) (dense)</td>
<td>Shallow foundation</td>
</tr>
<tr>
<td>HL1</td>
<td>( D_r = 60% ) (loose)</td>
<td>Shallow foundation</td>
</tr>
<tr>
<td>HL2</td>
<td>Shallow foundation</td>
<td></td>
</tr>
<tr>
<td>HL3</td>
<td>Shallow foundation</td>
<td></td>
</tr>
</tbody>
</table>

**Fig. 2** Picture of modeled sheet pile

**Fig. 3** Outline of horizontal reciprocal loading test
The relationships between the horizontal load $P$ and the horizontal displacement $\delta$ at the top of the pier are shown in Figs. 4 and 5. Figure 4 shows hysteresis curves, and Fig. 5 shows skeleton curves, which connect the turning points on each reciprocal cycle. The sheet-pile foundation (Cases HL2, HL3) has higher horizontal resistance than the shallow foundation (Cases HD1, HL1). Additionally, since the loop of the hysteresis curve for the sheet-pile foundation was larger than that for the shallow foundation, it was clear that the hysteresis damping of the former was larger than that of the latter. Moreover, the residual plasticity deformation of the sheet-pile model was unobservable after the experiment in the same way as in the vertical loading tests.

The settlement characteristic is related to an important function of the railway structure. Figure 6 shows the footing settlement when the horizontal displacement reached its peak in each reciprocal cycle. It can be seen that settlement increased with horizontal displacement in all cases. Although the shallow foundation for $D_r = 60\%$ (Case HL1) displayed a large settlement of more than 10% of the footing width, the sheet-pile foundation for $D_r = 60\%$ (Cases HL2, HL3) presented only a small settlement equivalent to that of shallow foundation for $D_r = 90\%$ (Case HD1). It is clear that the sheet-pile foundation restrained settlement.

Figure 7 shows the displacement of two cases (HL1 and HL2) computed by an image processing system. The small piece of line in the figure shows the locus of each target point until the horizontal displacement at the top of the pier reaches 20 mm. Displacement of the ground was observed in a large area around the modeled footing. However, the measurement and direction of displacement differed between the shallow foundation (Case HL1) and the sheet-pile foundation (Case HL2). With the former, the ground exhibited failure in the form of a circular slip over a comparatively limited domain shallower than 50 mm on both sides. The displacement of the ground around the edges of the footing model turned in the outward horizontal direction. For sheet-pile foundation on the other hand, the sheet piles restrained the horizontal deforma-
tion of the ground. Since deeper areas of the ground were deformed as a whole, it can be concluded that local failure of the ground did not occur.

3. Full-scale field test

3.1 Outline of full-scale models

Full-scale field tests aimed at practical use were conducted in Kawagoe City, Japan. The soil profile at the experiment site (outlined in Fig. 8) shows surface diluvial clay (Kanto loam) with a thickness of 5 m laid on a gravel layer. The models for shallow foundation and sheet-pile foundation shown in Figs. 8 and 9 were constructed with footings of 3.6 m in width and piers of 6 m in height. At 3.6 m, the sheet-pile length (which was the same as the width of the footing) did not extend as deep as the gravel layer.

3.2 Construction experiment

In the practical use of sheet-pile foundation, it is important to have a method of rigidly connecting sheet piles to the footing concrete. One simple method involves welding reinforced bars to the sheet piles to unify them with the footing concrete. However, with this method it can be very difficult to arrange the reinforced bars for the footing if the working space is very narrow.

A construction experiment using this method was therefore conducted to confirm the feasibility of arranging the footing bars. Figure 10 shows a photo of the work to weld reinforced bars to the sheet pile, and a photo of the finished state of arrangement. The experiment confirmed the feasibility of this method.

3.3 Horizontal static loading test

The horizontal static loading test was conducted by pulling the tops of the two models toward each other using a hydraulic jack. At first, the shallow foundation was pulled by the sheet-pile foundation, and the sheet-pile foundation was then pulled by the shallow foundation reinforced by a ground anchor as shown in Fig. 8.

The \( P-\delta \) relationship for each case is shown in Fig. 11, which also includes a photo of the final deformation of each model. The figure shows that the ratio of the horizontal resistance of the sheet-pile foundation against that of the shallow foundation was about four. This ratio was larger than that obtained in laboratory testing.

The results of measurement using a soil pressure gage buried under the footing are shown in Fig. 12. The distribution of vertical reaction stress on the shallow foundation is biased forward by an increase in the jack load. On the other hand, the bias of the reaction stress distribution is small in the sheet pile foundation.
Figure 10 shows the change in the axial force distribution of the sheet piles at the back and front sides. Axial compression force increases gradually in the front-side sheet piles, while axial tension acts on those at the back. Figure 14 shows the change in the bending moment distribution of the sheet piles at the back and front sides. The bending moment was the largest at a position of about 1.5 m in depth, but was sufficiently smaller than the yield bending moment.

Figure 15 shows the relationship between the jack load and the shear force at the head of the sheet piles. From this figure, it is clear that the shear resistance of the front-side sheet piles bears a large part of the shear resistance of the sheet pile foundation.

It is therefore clear that the sheet pile foundation has...
4. Conclusions

Based on the above, it has been shown that sheet-pile foundation offers excellent performance against seismic forces and can reduce the construction costs of foundation structures. At present, a design method has been established, and some railway bridges with sheet-pile foundations have already been constructed in Japan. It is expected that sheet-pile foundation will be used more widely in the future.

References

