Model tests on reinforcement effect of an anchorage work added to the existing anchored sheet pile wall

Essais modèles sur l'effet de renforcement d'un ouvrage d'ancrage ajouté à un mur en palplanches ancré existant

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ABSTRACT

Flexible bulkheads, such as anchored sheet pile walls, are often employed as earth retaining structures for port facilities in Japan. In recent years, existing anchored sheet pile walls have required reinforcement for maintenance and functional enhancement for large ships. To meet these requirements, a reinforcement method called dual-anchored sheet pile wall, in which additional anchorage work is attached to the existing anchored sheet pile wall, has been developed. The additional anchorage work has the same role as braces of an earth retaining wall, and is installed after deformation of the existing anchored sheet pile wall. However, braces are placed before deformation of the earth retaining wall. Therefore, the loading histories of backfill of the dual-anchored sheet pile wall and the retaining wall are different. The additional anchorage work cannot be designed in the same manner as earth retaining wall braces. In this study, model tests of the dual-anchored sheet pile wall were conducted to understand its behaviours. This paper describes the effects of the additional anchorage work to reduce the load acting on the existing anchored sheet pile wall, such as the bending moment of the sheet pile.

RÉSUMÉ

Des cloisons étanches flexibles, tels que des mur en palplanches ancrés sont souvent employées pour le soutènement des installations portuaires au Japon. Récemment, il a été requis que des mur en palplanches existants soient renforcés à des fins de maintenance, et améliorés d'un point de vue fonctionnel pour des vaisseaux de grandes dimensions. Afin de répondre à cette requête, une méthode de renforcement appelée mur en palplanches doublement ancré a été dévelopée, dans laquelle un ouvrage d'ancrage supplémentaire est attaché au mur en palplanches ancré existant. L'ouvrage d'ancrage supplémentaire joue le même rôle que les etrésillons dans un mur de soutènement. L'ouvrage d'ancrage supplémentaire est construit après la déformation du mur en palplanches ancré existant. En revanche, les etrésillons sont construits avant la déformation d'un mur de soutènement. En conséquence, l'évolution temporelle sous charge en remblai n'est pas la même pour le mur en palplanches doublement ancré et un mur de soutènement. L'ancrage supplémentaire ne peut pas être réalisé de la même manière que les etrésillons d'un mur de soutènement. Dans cette étude, des essais modèles du mur en palplanches doublement ancré ont été effectués afin de comprendre son comportement. Cet article décrit l'effet de l'ouvrage d'ancrage supplémentaire afin de réduire la charge s'exerçant sur le mur en palplanches ancré existant, tels que le moment fléchissant des palplanches.

Keywords : sheet pile wall, two-dimensional model test, aluminium layered ground, bending moment

1 INTRODUCTION

A flexible bulkhead, such as an anchored sheet pile wall, is often employed as an earth retaining structure for port facilities in Japan. For the quay walls with large depth, the availability of reinforcement by adding an anchorage to the existing anchored sheet pile wall (dual-anchored sheet pile wall) has been proposed (Ishiguro, 1963; Ishiguro and Takahashi, 1992). An example of dual-anchored sheet pile walls is shown in Figure 1. The additional anchorage, however, was difficult to construct, and its design method has not been established. Therefore, the dual-anchored sheet pile wall has not been applied. Sheet piles with high tensile strength were developed and applied to large-scale quay walls, instead of the dual-anchored sheet pile wall. In recent years, existing anchored sheet pile walls have required reinforcement for maintenance and functional enhancement for large ships. To meet these requirements, a reinforcement method called dual-anchored sheet pile wall, in which additional anchorage work is attached to the existing anchored sheet pile wall, has been developed.

The additional anchorage work has the same role as braces of an earth retaining wall. The additional anchorage work is installed after deformation of the existing anchored sheet pile wall. However, braces are placed before deformation of the earth retaining wall. Therefore, the loading histories of backfill of the dual-anchored sheet pile wall and the retaining wall are different. The additional anchorage work cannot be designed in the same manner as braces of earth retaining walls. In the design of a flexible bulkhead, such as an anchored sheet pile wall, the interaction between the structure and the ground is important. The Technical Standards and Commentaries for Port and Harbour Facilities in Japan (Ports and Harbours Bureau, 1999) describes the design method for anchored sheet pile walls based on the theory of beams on elastic material. The validity of this

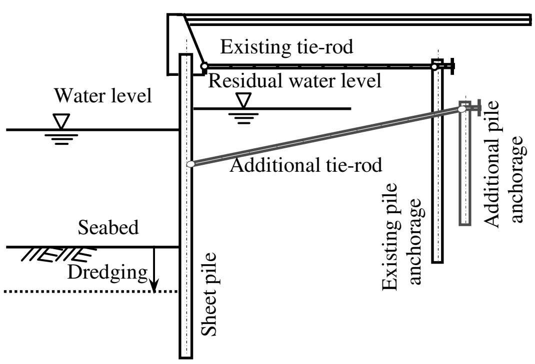

Figure 1. Example of dual-anchored sheet pile wall

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method was confirmed by comparing the results of experiments (Tchebotarioff, 1949) and field observations (Takahashi et al., 1993). However, it has not been investigated in sufficient detail.

In this study, model tests of the dual-anchored sheet pile wall were conducted to investigate the effects of the additional anchorage on the bending moment of the sheet pile and the reaction of backfill.

2 MODEL TESTS

2.1 *Model of dual-anchored sheet pile wall*

The two-dimensional model test, which is free from the effects of wall friction, is available for understanding the behaviour of structures such as sheet pile walls. In this study, therefore, aluminium rods 15 cm in length and 1.5, 2 and 3 mm in diameter were used as model ground material. The aluminium rods of different diameters were uniformly mixed in weight ratios of 1:1:1. The cross-section of the dual-anchored sheet pile wall model is shown in Figure 2. The model was made in the frame of H beams constructed in the large-scale soil pit 3 m in width, 6 m in length and 3 m in depth. To avoid friction between the frame and model ground, acrylic plates were attached to the frame on both sides. The width of the model ground was 2.6 m. The height of the model ground in front of the sheet pile wall was 1.4 m and equal to the embedded length of sheet pile. The difference of the height between both sides of the sheet pile was 1.0 m.

The tie rods were difficult to model in the model ground made of aluminium rods. In addition, the behaviour of anchorage pile complicates the test conditions. Therefore, the tension of tie rods was modelled by loading from the sea side. The upper blade as the existing anchorage was set and fixed at the same height as the backfill. The lower blade as the additional anchorage was set at the loading position designated in each case. In this study, a series of tests on the different loading positions were conducted. The lower blades of all cases are shown in Figure 3 to specify the loading positions. The loads of anchorages were measured by load cells attached behind the upper and lower blades.

2.2 *Model of sheet pile*

The sheet pile was a steel plate of length 3.1 m, width 15 cm, and thickness 6 mm. Strain gauges were attached to both sides of the sheet pile, as shown in Figure 3. To protect the strain gauges, both sides of the sheet pile were coated with epoxy resin, except for the loading positions of the front surface. The coated sheet pile was calibrated by loading test in which it was used as a simple beam. The calibration was carried out on both sides of the sheet pile. The flexural rigidity of the coated sheet pile was 560 Nm^2.

2.3 *Procedure of model tests*

Before making the model ground, the sheet pile was set perpendicularly at the centre of the bottom frame in the longitudinal direction and the pile head was fixed to the upper frame. The upper blade was set and fixed at this time. Then, the bottom frame was covered with a row of aluminium rods 3 mm in diameter. These aluminium rods were fixed with adhesive to restrict lateral displacement of the bottom of the sheet pile. (Rotation of the bottom end of the sheet pile is permitted.)

The sheet pile wall can be constructed by two methods: the dredging method in which the ground in front of the sheet pile is excavated, and the reclamation method in which the ground is filled in behind the sheet pile. Kikuchi and Mizutani (2003) conducted a series of model tests on a sheet pile wall, and showed that the distribution of earth pressure acting on the sheet pile was unaffected by ground construction method. In this study, a model of a dual-anchored sheet pile wall was made by

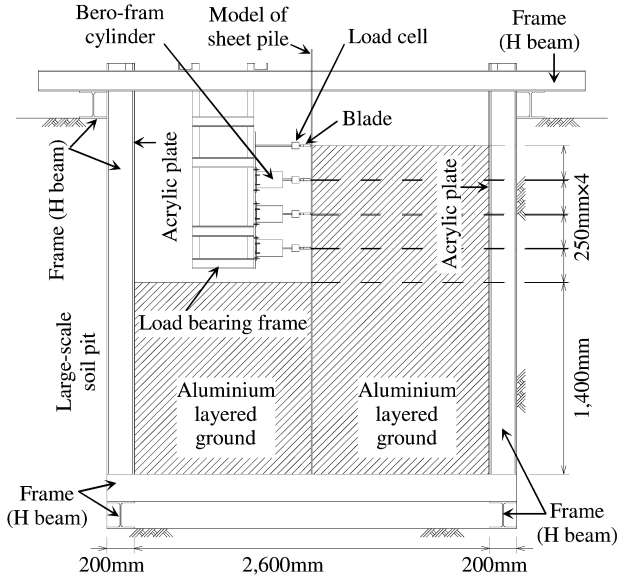


Figure 2. Model of dual-anchored sheet pile wall

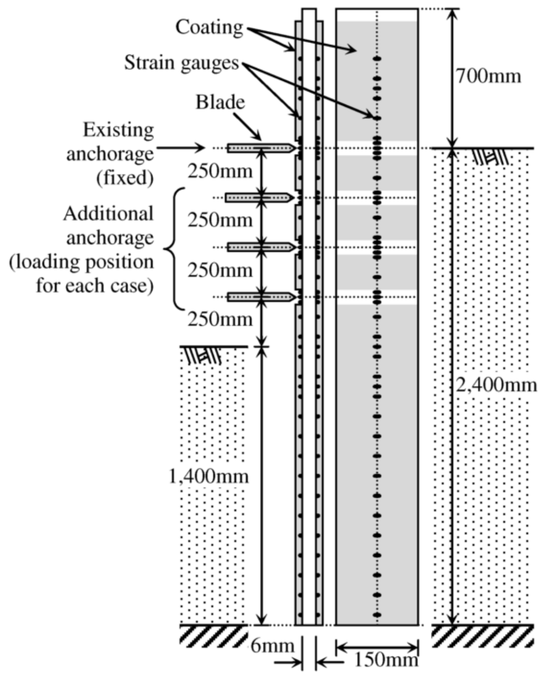


Figure 3. Cross section and front of sheet pile model

the reclamation method, because the equipment for loading were located in front of the sheet pile, as shown in Figure 2. The foundation ground and the backfill were made by accumulation of aluminium rods. The height and weight of the accumulated aluminium rods were managed in each layer 10 cm in thickness to achieve uniform ground. The density of the model ground was set as 2.1 g/cm^3. The foundation ground 1.4 m in height was made on both sides of the sheet pile taking care to avoid deformation of the sheet pile, which was managed by measuring strain. Backfilling was subsequently carried out up to a height of 2.4 m. The sheet pile was supported from the front during backfilling to avoid deformation. Fixed and supported parts of the sheet pile were released after backfill.

The lower blade as an additional anchorage was placed at the designated height. The heights of the lower blade in Cases 1-3 were 25 cm, 50 cm, and 75 cm from the foundation ground, respectively. After completion of the model of the dual-

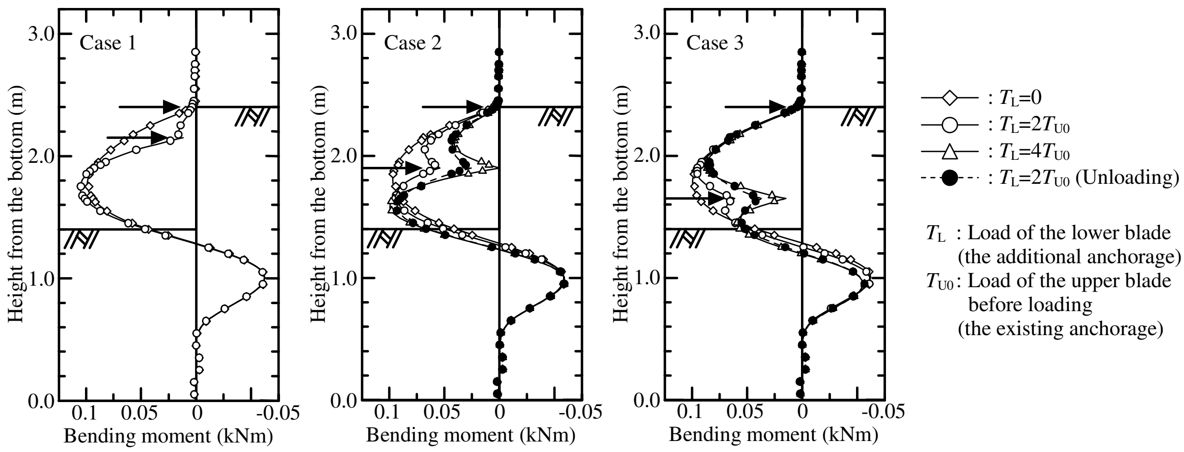


Figure 4. Changes in distributions of the bending moment induced by loading of the additional anchorage

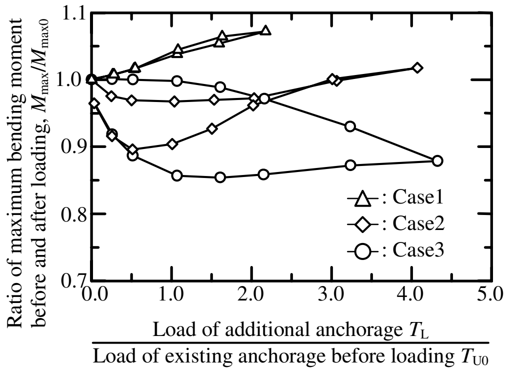
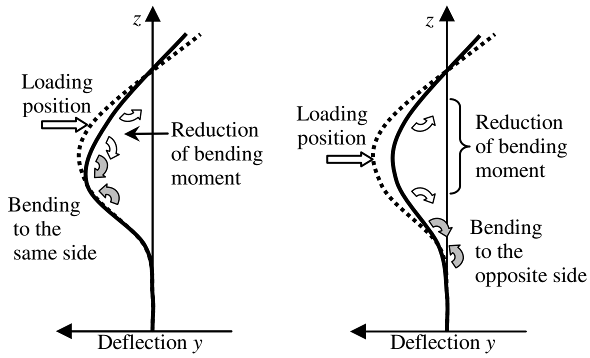


Figure 5. Change in the maximum bending moment induced by loading of the additional anchorage



(a) The case where the loading position is high

(b) The case where the loading position is low

Figure 6. Difference in the change of deflection of sheet pile caused by the loading position

anchored sheet pile wall, loading and unloading of the lower blade (the additional anchorage) were carried out.

3 TEST RESULTS

Changes in the distributions and maximum values of the bending moment of the sheet pile induced by loading of the additional anchorage are shown in Figures 4 and 5. The approximation curves of the bending moment are also shown in Figure 4. The approximation was made using the cubic spline function. The approximation curve did not have to coincide with the scattered data plot because the test results will inevitably contain some errors. Therefore, the smoothing spline function was used. The distributions of the bending moment cannot be smoothed at the loading position of the additional anchorage, as it must be undifferentiable at that position. The smoothing spline function was applied separately to the part above the loading position of bending moment distribution and the lower part. The bending moment at the loading position was assumed so that it may satisfy the following conditions.

(1) The load of the additional anchorage should be equal to the discontinuity of shear force at the loading position obtained by differentiation of the bending moment distribution.

(2) The reaction of the ground obtained by differentiation of shear force distribution should be continuous at the loading position. (However, its derived function can be discontinuous.)

Figure 4 shows that the bending moment around the loading position was reduced and that the bending moment of the part 20 cm deeper than the loading position was increased in all cases. The maximum bending moment was reduced in Cases 2 and 3, whereas it was increased in Case 1. These results were thought to be due to the differences in change of deflection of the sheet pile. In the case where the loading position is high, the part lower than the loading position of the sheet pile is bent further to the same side before loading, as shown in Figure 6 (a). The bending moment of this part is relatively large, and the position of the maximum bending moment before loading may be contained in this part. Therefore, the maximum bending moment is increased by loading, as illustrated by Case 1 in Figure 5. In Case 1, the load of the additional anchorage is thought to reduce the load of the existing anchorage because the two anchorages are close to each other (Morikawa and Kikuchi, 2007). In the case where the loading position is low, the bending moment of the part lower than the loading position is also increased. However, this part is bent to the opposite side before loading, as shown in Figure 6 (b). The bending moment of this part is relatively small or negative. Thus, the maximum bending moment can be reduced, as illustrated by Cases 2 and 3 in Figure 5. These results indicated that the additional anchorage close to the position of the maximum bending moment, such as those in Cases 2 and 3, is advantageous for reduction of the bending moment. In Case 2, the loading position was close to the position of maximum bending moment before loading, but higher than that position. Therefore, the initial bending moment to be increased was larger than that of Case 3, and the bending moment was increased when the load became large.

Changes in deflection of the sheet pile and reaction of the model ground induced by loading of the additional anchorage of Case 3 are shown in Figure 7. The reaction of the model ground can be obtained by differentiating the spline curve of the bending moment twice. In this study, however, the distribution of the shear force was also evaluated by the cubic spline

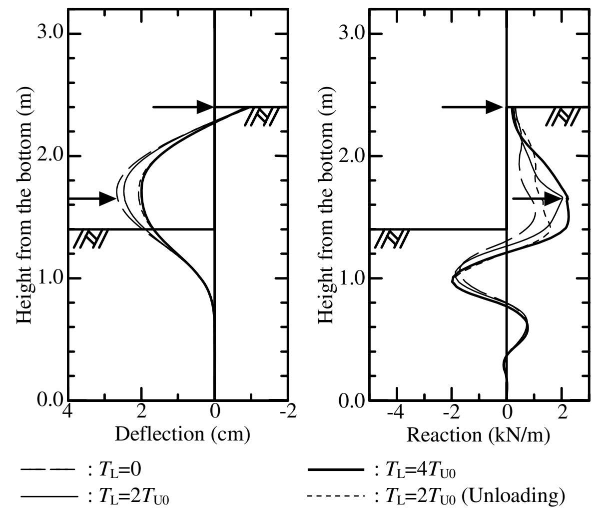


Figure 7. Changes in deflection and reaction induced by loading of the additional anchorage (Case 3)

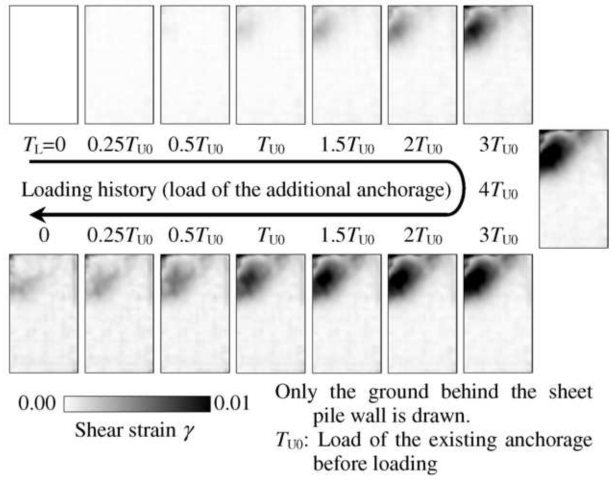


Figure 8. Contours of shear strain of model ground behind the sheet pile wall (Case 2)

function before it was differentiated to calculate the reaction of the model ground (Kikuchi, 2003). This calculation was conducted to maintain the degree of the spline function. The deflection of the sheet pile was obtained by twice trapezoidal integration of the moment distribution because the degree of the spline function is not reduced by integration.

From the changes in deflection of the sheet pile shown in Figure 7, the deflection was hardly changed from the maximum load $T_L=4T_{U0}$ to $T_L=2T_{U0}$ of unloading. It was also observed that the deflection at $T_L=2T_{U0}$ of unloading was smaller than that at $T_L=2T_{U0}$ of loading. This result corresponds to that shown in Figure 5 indicating that the bending moment during unloading is smaller than that during loading in Case 3. Figure 8 shows contours of shear strain of the model ground behind the sheet pile wall evaluated from photographs taken at each loading step. Residual strain can be observed in a contour of the unloading step as compared with that of the loading step at the same load. This result also corresponds to those of Figures 5 and 7.

On the other hand, the changes in reaction of the model ground in Figure 7 indicate that the reaction at $T_L=2T_{U0}$ of unloading becomes smaller than that at $T_L=2T_{U0}$ of loading. Furthermore, the reaction was decreased from the maximum load $T_L=4T_{U0}$ to $T_L=2T_{U0}$ of unloading, whereas the deflection was hardly changed. The backfill of an earth retaining wall reaches the active state even if the forward displacement of the wall is small, although the large backward displacement of the wall is required to make backfill be in the passive state. This is similar to the results of the reaction shown in Figure 7. This result implies that the effect of reduction of the bending moment of the sheet pile can be increased if a large load is applied before the designated load.

4 CONCLUSIONS

In this study, model tests of the dual-anchored sheet pile wall were conducted to understand its behaviours. The following conclusions were derived from the results.

The bending moment of the sheet pile can be reduced by additional anchorage work. The reduction effect of the bending moment depends on the position of the additional anchorage.

When the position of the additional anchorage is relatively high, the bending moment cannot be reduced because the part lower than the loading position of the sheet pile is bent further to the same side before loading. The load of the additional anchorage is thought to work for reduction of the load of the existing anchorage.

When the position of the additional anchorage is relatively low, the bending moment can be reduced because the part lower than the loading position of the sheet pile is bent to the opposite side before loading. The maximum bending moment can also be reduced. Thus, the additional anchorage close to the position of the maximum bending moment is advantageous for reduction of the bending moment.

The bending moment during unloading is smaller than that during loading. This result can be understood by relating to changes in deflection of the sheet pile, the reaction of the model ground, and the residual strain of the model ground behind the sheet pile wall. Furthermore, this result implies that the reduction effect of the bending moment of the sheet pile can be increased if a large load is applied before the designated load.

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