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FEM analysis of excavation with soils improved in its passive zone

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ABSTRACT: To improve the behavior of the excavation, the technique of improvement of the soil in its passive zone has often been used. While the effectiveness of this technique has widely been proved, no design concept about the shape and the scope of the treated soil in the passive zone has been established at this time. In this paper, the finite element method was used to analyze behaviors of excavations with varied widths and depths of the treated area in the passive zone, and some valuable conclusions were obtained. Based on this study, a method for evaluating the scope and the shape of the treated area in the passive zone was then proposed.

1 INTRODUCTION

The stability and the ground settlement associated with deep excavations have a very close relationship with the type of retaining system, the excavation procedure, the properties of soils and so on. Among these factors, the properties of soils in which the retaining wall embeded are most important. The soils at the excavation side of the wall provide passive earth pressure and are defined as passive zone. By jet grouting or deep mixing, the soil in the passive zone can be well improved to provide much more soil resistance, which is beneficial for improving mechanical behaviors of the retaining wall and other characteristics of the excavation. It has been shown that soil treatment in the passive zone is more effective for the excavations than that in the active zone (Cai 1994), which locates behind the retaining wall. Soil improvement in the passive zone is an effective and economical technique for the excavations, since it is efficient to reduce the ground settlement induced by the excavation, the horizontal displacement of the retaining wall, the excavation base heave, and the strut force etc. To some extent, the technique is also helpful for preventing deep excavation from piping failure or shearing failure of soils in the passive zone.

Although the technique of soil improvement in the passive zone has been widely used in deep excavations and its effectiveness has also been verified by a large number of successful excavation projects (Gaba 1990; Ou et al. 1996; Ying 1997), the analysis method and design concept are still highly empirical and there is no an explicit methodology now. Especially, it is difficult to evaluate reasonably the scope and the shape of the treated area according to available theoretical basis at this time. In this paper, the finite element method was used to study behaviors of excavations with soils improved in the passive zone. Behaviors of both cantilever and single braced excavations with various scopes and shapes of treated soils in the passive zone were analyzed, and some valuable conclusions were obtained. Based on this study, a design method about the reasonable scope and shape of the treated area was presented.

2 FEM ANALYSIS OF EXCAVATION

A two-dimensional finite element program for deep excavations (Wang 1998) was used as a basic research tool in this paper. In this program, the eight-node isoparametric plane element was selected for the soil and the retaining wall, and the bar element was adopted for the strut. At the interface between the soil and the wall, the interface element without thickness proposed by Goodman (1968) was used. The retaining wall and strut responses were assumed to be linear-elastic. The hyperbolic model proposed by Duncan and Chang (1970) was utilized to model the soil behavior.

The period of most excavations is usually short. Therefore, the excavations were assumed to be analyzed with undrained conditions. For this reason, the program was formulated based on the total stress analysis.

In order to simulate excavation process, the stiffness of every element representing soil removed due to excavation was set to zero, and the nodes of these elements were hinged, while the finite mesh keeps unchanged. The equivalent nodal forces corresponding to these elements were calculated as follows (Ghaboussi

& Pecknold 1984):

$$\{f\} = \int [B]^T \{\sigma\} dV - \int [N]^T \{\gamma\} dV \tag{1}$$

where $\{f\}$ = equivalent nodal forces; $[B]$ = strain-displacement transformation matrix; $\{\sigma\}$ = stress vector; $[N]$ = displacement shape function; $\{\gamma\}$ = vector of unit weight of soils.

3 CANTILEVER EXCAVATION

Cantilever excavation (Fig. 1) was firstly selected to study in the paper. With the finite element program, the influences of width B_r and depth H_r of the treated zone on the horizontal displacement of wall, ground settlement and the excavation base heave can be carefully investigated.

As is shown in Figure 1, the width B of the cantilever excavation was 40 m and the maximum excavation depth H was 4 m. The retaining wall is 35 cm thick and 10 m deep. It was assumed that the Young's modulus of the wall was 21,000 MPa and the subsoil stratum was mainly composed of low-to-medium plasticity silty clay. In order to save computation time, treated and untreated soils were assumed to be linear-elastic. The properties of treated and untreated soils are listed in Table 1.

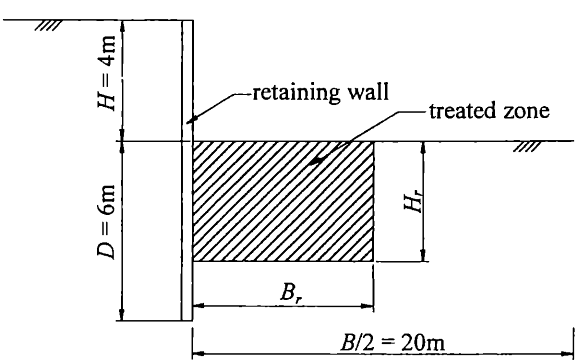

Figure 1. Cantilever excavation with soil improvement in the passive zone.

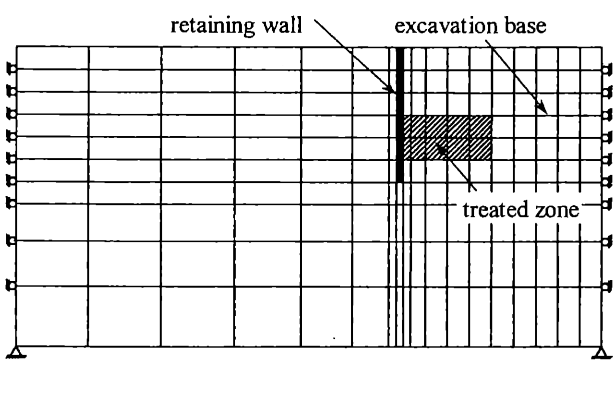

Figure 2. Finite element mesh for cantilever excavation analysis.

Figure 2 shows the finite element mesh for the cantilever excavation with soil improvement in the passive zone. It was assumed that the vertical boundaries were supported with rollers and the base was supported with hinges.

3.1 *Maximum horizontal wall displacement*

The maximum horizontal displacement occurs on the top of the wall for cantilever excavation. Figure 3 shows the variation of maximum horizontal wall displacements with different depths or widths of treated soils in the passive zone.

Table 1. Soil properties.

Soil layer	Depth (m)	γ (kN/m³)	c (kPa)	φ (°)	E (MPa)	ν
1	0 - 4	16.8	8	7	5	0.45
2	4 - 10	17.0	17	20	12	0.39
3	≥ 10	17.0	18	25	18	0.35
Treated soils	-	17.0	200	30	40	0.30

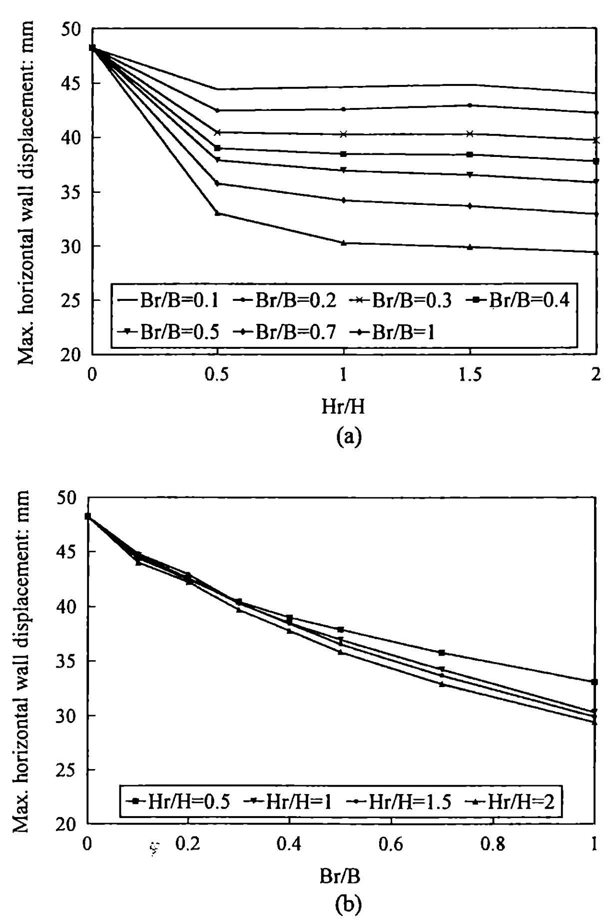

Figure 3. Variation of maximum horizontal wall displacement with increase in (a) treated depth H_r and (b) treated width B_r for various treated areas, H = excavation depth, B = excavation width.

As can be seen from Figure 3(a), although enlarging depth of treated soils can reduce the maximum horizontal wall displacement, the magnitudes are much dependent on the width of treated area. For a small width of treated area, an increase in the depth of treated area does not reduce the maximum horizontal wall displacement evidently. For a relatively large width of treated area, it turns to be effective to reduce the wall displacement. It can also be found that the maximum horizontal wall displacement reduces obviously when the treated depth H_r reaches 50 percent of the excavation depth H. However, when the depth H_r continues to be enlarged, the curves become to be close to a horizontal line, indicating that there is no further benefit to reduce the displacement. Therefore, concerning on the efficiency and economization, the treated depth H_r should not be larger than half of the excavation depth H in design.

As is shown in Figure 3(b), it is effective to reduce the maximum horizontal wall displacement by increasing the width of treated area. If the treated area B_rH_r remains unchanged, for example, $B_rH_r = 0.5BH$, the maximum horizontal wall displacement for the case $B_r = B$ and $H_r = 0.5H$ is about 33 mm as shown in Figure 3(b). For the case $B_r = 0.5B$ and $H_r = H$, as shown in Figure 3(a), the wall displacement is close to 37 mm. It can then be concluded that enlarging the width of the treated area is more efficient than enlarging the depth to reduce the horizontal wall displacement.

In conclusion, the treated soils behave just like an imaginary strut and enlarging the width of the treated area can reduce the horizontal wall displacement evidently.

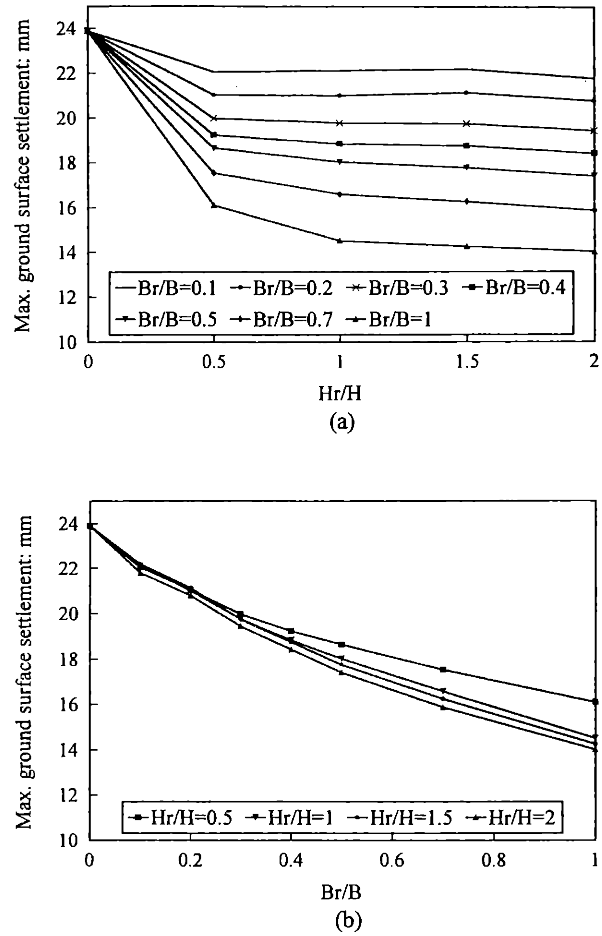

Figure 4. Variation of maximum ground surface settlement with increase in (a) treated depth H_r and (b) treated width B_r for various treated areas, H = excavation depth, B = excavation width.

3.2 *Ground surface settlement*

Figure 4 shows the influences of depths and widths of treated soils in the passive zone on the maximum ground settlement.

From Figure 4(a), it can be seen that the maximum ground settlement decreases with the increase in the depth of treated soils. However, the decreasing magnitudes are affected by the treated width. For smaller widths of the treated areas, the reductions of ground settlement are also smaller. For larger treated widths, the reductions become relatively greater as well. In addition, when the treated depth H_r approaches 50 percent of the excavation depth H, the maximum ground settlement is reduced evidently. While enlarging the treated depth continually, it contributes little to reduce the ground settlement. Therefore, it is suggested in design work that the appropriate treated depth H_r should be half of the excavation depth H for cantilever excavations.

It can be seen from Figure 4(b) that enlarging the treated width is always effective to reduce the ground settlement. It can also be found from Figure 4 that enlarging the treated width is more efficient than enlarging the depth to reduce the ground surface settlement for cantilever excavations.

3.3 *Excavation base heave*

The results of finite element analyses indicate that the excavation base heave increases with the increase of the distance away from wall, and reaches to its maximum value at the center of the excavation. Figure 5 shows the variation of excavation base heave with varied treated depths for the treated width B_r = 10 m and B_r = 20 m.

As can be seen from Figure 5, the excavation base heave within the treated zone reduces evidently, but the heave outside the treated area is affected slightly. If the treated width is equal to the excavation width, that is B_r = 20 m, the heave within the total excavation area reduces obviously. For a fixed treated width, it can be found that enlarging the treated depth can reduce the excavation base heave to some extent, but the reduction efficiency depends on the width of treated soils. For a small treated width, choosing the largest treated depth merely contributes to reduce the heave within a little scope. For this reason, a relatively large width of the treated area should be adopted primarily, and an appropriate depth of the treated soils should be subsequently taken into account in the design process.

4 SINGLE BRACED EXCAVATION

Single braced excavation with varied depths and widths of treated soils in the passive zone was also studied in this paper. The width and the depth of the excavation are 40 m and 5 m respectively. The excavation was completed in two excavation stages: (1) excavation down to 1.5 m below the ground surface; (2) install the strut at the ground surface level and then excavate to 5.0 m. The axial stiffness of the strut was assumed to be 32,130 kN/m/m. The other parameters were assumed to be the same as those for the previous cantilever excavation.

According to the results of the finite element analyses, the influences of widths and depths of the treated zone on the wall displacement, ground settlement and base heave for the single braced excavation were similar to those for the cantilever excavation. The details of these behaviors will not be presented here. Only some valuable conclusions were given as follows.

The maximum horizontal wall displacement occurs approximately at the excavation base for the single braced excavation. Enlarging the treated width or depth can reduce the horizontal wall displacements, but increasing the width is more effective than increasing the depth. In addition, when the treated depth H_r approaches 60 percent of the excavation depth H, keeping on enlarging the treated depth will do little to reduce the wall displacements. Therefore, it is believed that the most reasonable treated depth should be 60 percent of the excavation depth.

Table 2 lists the variations of the axial force of strut with varied treated widths (B_r) and depths (H_r). It can be seen that the axial force of the strut keeps on decreasing while enlarging the treated width or depth. If the area of the treated zone is assumed to be a fixed value, for example, $B_r \times H_r = 40$ m^2, the axial force of the strut is 923.1 kN for the case $B_r = 10$ m and $H_r = 4$ m from Table 2. However, for the case $B_r = 20$ m and $H_r = 2$ m, the axial force of the strut is decreased to 784.9 kN. It can therefore be concluded from the results that enlarging the treated width is more effective than enlarging the depth to reduce the axial force of the strut.

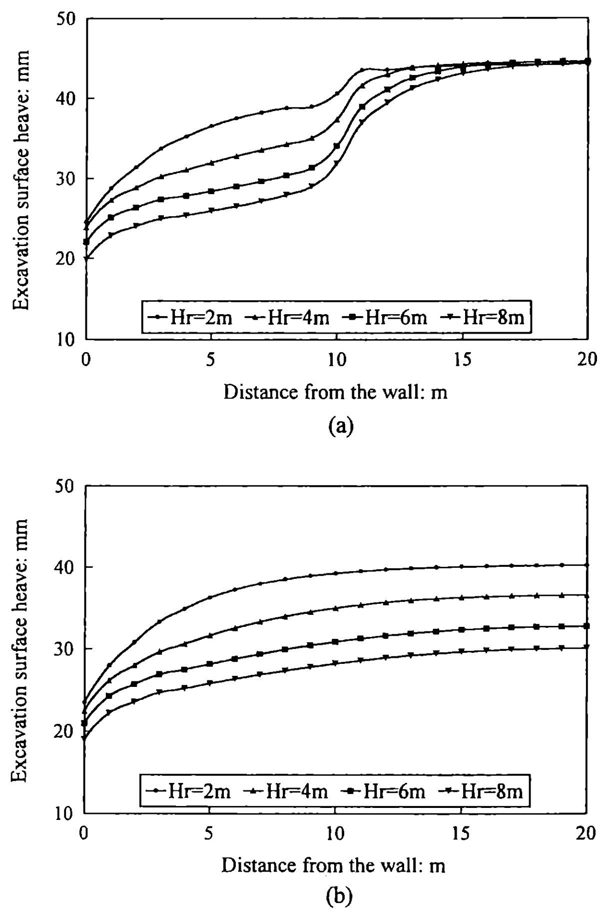

Figure 5. Variation of excavation base heave with increase in distance from wall for the treated width (a) $B_r = 10$ m and (b) $B_r = 20$ m with various treated depths.

5 SHAPES OF THE TREATED ZONE

The reasonable shape of the treated zone was finally investigated in this paper. Figure 6 shows various shapes of treated soils in the passive zone for cantilever excavations. All of these cases have a same treated area of 24 m^2. Therefore, the cost of the soil improvement in passive zone for these cases is all the same.

Table 2. Variations of the axial force of strut for various widths and depths of the treated area.
(The axial force of strut: kN; B_r: m; H_r: m.)

	$B_r=0$	$B_r=2$	$B_r=4$	$B_r=6$	$B_r=8$	$B_r=10$	$B_r=14$	$B_r=20$
$H_r=0$	1176.6	1176.6	1176.6	1176.6	1176.6	1176.6	1176.6	1176.6
$H_r=2$	1176.6	1100.1	1080.5	1044.9	1010.2	978.7	914.4	784.9
$H_r=4$	1176.6	1108.8	1067.4	1024.9	966.1	923.1	845.3	707.5
$H_r=6$	1176.6	1113.3	1070.9	1018.8	956.2	908.0	828.3	697.9
$H_r=8$	1176.6	1097.6	1055.1	1000.2	933.7	882.0	799.1	683.1

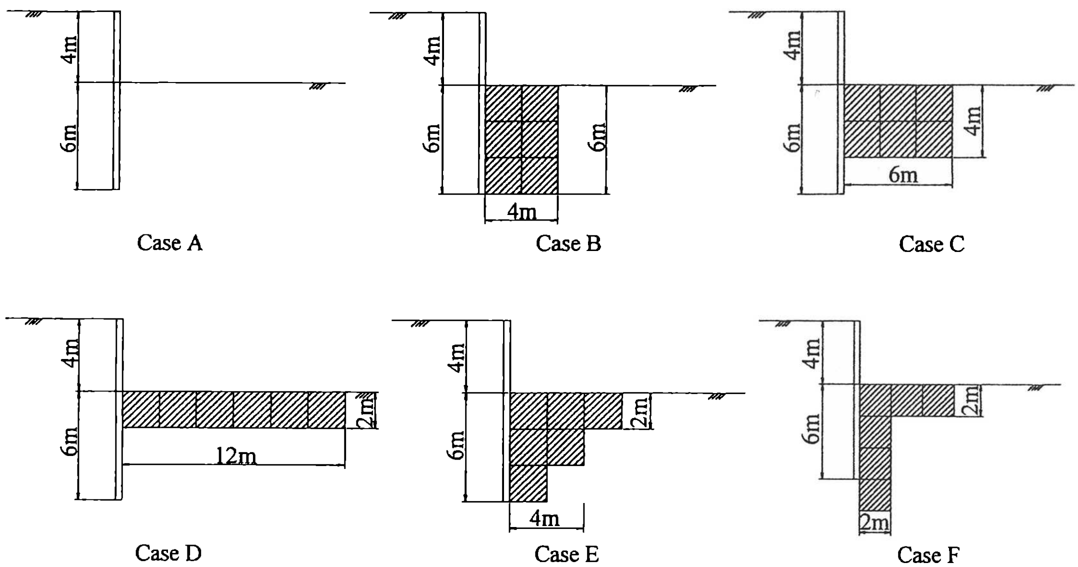

Figure 6. Various shapes of the treated zone.

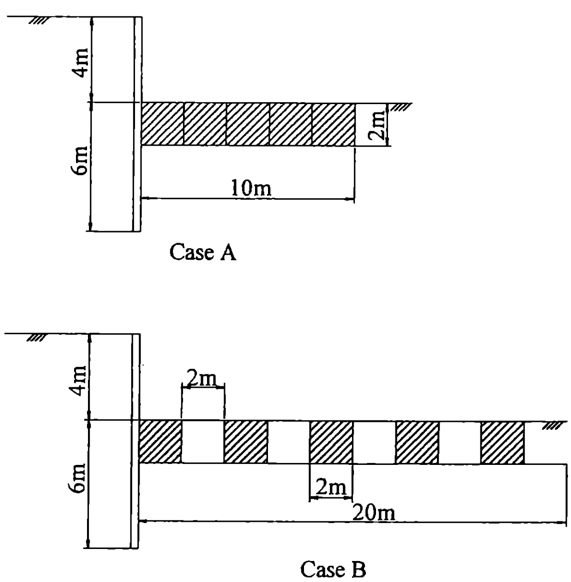

Figure 7. Continuous and discontinuous shapes of the treated zone.

It can be found by the finite element analyses that case D is the most efficacious one to reduce the wall displacement, ground settlement and base heave while case B is the most ineffective one. The effects of case C, E and F are almost the same. The treated width of case D is the largest in all the cases, and its treated depth of 2 m has also been reached 50 percent of the excavation depth which is 4 m. Therefore, based on the previous studies, case D is most reasonable. The treated width of case B is smallest while its treated depth is largest, but it is still most inefficacious. This is just because that the treated depth has gone beyond a half of the excavation depth greatly, and the excessive depth contributes little to improve the behavior of the excavation. The treated widths of case C, E and F are all same. Although the shapes and depths of these cases are different, there are no obvious differences for improving the behavior of the excavation. In conclusion, the width of the treated zone should be enlarged as possible as can when an appropriate treated depth has been selected.

The continuous and discontinuous shapes of the treated zone as shown in Figure 7 were also studied in this paper. The results of the finite element analyses indicate that the continuous one is better than the discontinuous one to improve the behavior of the excavation.

6 CASE STUDY

A deep excavation case history for a 28-story residential building located at Hangzhou of China was analyzed. From the soil investigation, there is a 2 m thick layer of fill underlain by a mucky clay with an average thickness of 20 m. It is a 173.3 m × 29 m rectangular excavation. The maximum excavation depth is 7.1 m below the ground surface. The driving casing cast-in-place piles with diameters of 426 mm and center-to-center spacing of 1.0 m were used as the retaining structure. The excavation was completed in two stages: (1) excavation down to 4.5 m below the ground surface; (2) install the strut at 3.5 m and then excavate to 7.1 m.

To improve the behavior of the excavation, the soil improvement was used throughout the passive zone. The width of the treated area was 29 m, and the treated depth was 4 m.

The description of each soil layer and the material properties are listed in Table 3. The Young's modulus of the retaining wall was 24,000 MPa and the axial stiffness of the strut was 24,621 kN/m/m.

Table 3. Soil properties.

Soil layer	Depth (m)	γ (kN/m^3)	c (kPa)	φ (°)	E (MPa)	ν
1	0 - 2	19.2	24.0	24.8	8	0.32
2	2 - 24	18.0	17.7	11.4	7	0.35
3	≥ 24	18.2	29.0	12.8	10	0.30
Treated soils	-	17.0	200.0	30.0	40	0.25

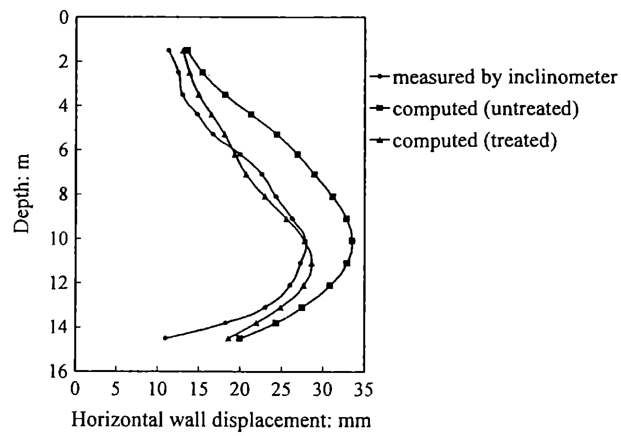

Figure 8. Comparisons of measured and computed horizontal wall displacements.

The finite element program was used to study the case. The comparisons of field measurements and computed results for the horizontal wall displacements are shown in Figure 8. Moreover, the case without taking account of the treated area has been investigated, and the computed results are also shown in Figure 8. It can be seen that the computed displacements are close to those obtained from field measurements.

In the case, the treated width B_r is equal to the excavation width B, and the treated depth H_r also approaches to 60 percent of the excavation depth H. Based on the previous studies, it is known that the treated area is reasonable. Therefore, the soil improvement in the passive zone in the case is obviously effective to reduce horizontal wall displacements, as can be seen from Figure 8.

7 CONCLUSIONS

The behaviors of cantilever and single braced excavations with various widths and depths of treated soils were studied by the finite element method. The results indicate that enlarging the treated width or depth is useful for reducing the wall displacement, ground settlement, excavation base heave and strut forces, but enlarging the treated width is more efficacious. The width of the treated area B_r should be selected relatively large, and the shape of the treated zone should be continuous. For a cantilever excavation, there is no need for the depth H_r to be larger than half of the excavation depth. For a single braced excavation, the depth H_r should not exceed 60% of the excavation depth.

These conclusions can not be regarded as completely general because it does not consider all the factors affecting excavation behavior such as excavation depth, soil type, excavation sequence, penetration depth of retaining wall, and so on. However, the conclusions might be applicable to the other excavation cases with similar excavation conditions.

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