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Analysis on influence of retaining wall deflection and ground settlement caused by Top-down and Bottom-up excavation methods

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ABSTRACT: In this study, six cases of deep-excavation in Taipei are collected. Three cases of Top-down construction method and three cases of Bottom-up construction method are considered. The software RIDO is used to compare Top-down construction and Bottom-up construction methods with analyzed values. The results obtained show that diaphragm walls with buttress walls or cross walls and different types of buttress walls would influence the amount of wall displacement and ground settlement during excavation. According to the conditions of wall displacement and ground settlement induced by the two methods, questions arising have to be understood and solved. For example, the effects of the connecting interface when the diaphragm walls and the buttress walls are constructed have to be considered while construction is being undertaken. The displacement amount of the walls induced by the creeping of clay during the period of curing of the constructed slabs must also be considered. Based on the considerations mentioned above, the relationship between the maximum lateral deformation of diaphragm wall and maximum ground settlement with respect to the depth of the excavation are discussed.

RÉSUMÉ : Dans cette étude, six cas d'excavation profonde à Taipei sont analysés. Trois cas d'approche descendante et troi cas d'approche ascendante sont considérés. Le logiciel RIDO est utilisé pour comparer les constructions avec approches ascendantes et descendantes. Les résultats obtenus montrent que les parois moulées avec murs en contrefort ou des murs de refend influencent la quantité de déplacement de la paroi ainsi que le tassement du sol lors de l'excavation. En fonction des conditions de déplacement de la paroi ainsi que le tassement du sol induit par les deux méthodes, des questions se posent et doivent être comprise et résolues. Par exemple, les effets des interfaces de liaison lots de la construction des parois moulées et contreforts murs, le déplacement des murs induits par le glissement d'argile pendant la période de durcissement des dalles, la forme et dimension des entretoises, l'espace, des tonnes de précontrainte doivent être considérées avant que la construction ne soit exploitée. Sur la base des considérations mention nées ci-dessus, la relation entre la déformation latérale maximale de la paroi de la membrane et le tassement du sol maximal p ar rapport à la profondeur de l'excavation sont discutés.

KEYWORDS: deep-excavation, diaphragm wall, buttress wall, displacement and settlement, Top-down construction, creep.

1 INTRODUCTION.

In this study, the buttress model for analysis and design, proposed by Hsieh and Lu (1999), is used to calculate proper values for soil parameters. An empirical nomogram of maximum wall deflection and maximum ground settlement caused by deep excavation, developed by Ou (2002), is compared with the computed results of this study to explore the wall deflection and ground settlement using different excavation retaining methods. In the analysis, the soil parameters are input according to the drilling test results and the analysis results are compared with the measured data to check the load of retaining wall deflection, internal temporary strut, and diaphragm wall with strut. Some of the parameters are modified to match the wall deformation. Among all the influencing factors, soil parameters are the dominant ones.

2 EFFECTS OF TOP-DOWN AND BOTTOM-UP EXCAVATION METHODS ON WALL DEFORMATION

2 .1 *Case I (Top-down)*

In Case I, a five-floor underground excavation is conducted with an excavation depth of 21.1 m, a diaphragm wall thickness of 1.2 m. and a wall depth of 43 m. The construction site in this case has a strip topography with a length of approximately 143 m, width of about 38 m, and an area of about 6,373m^2 . On this basis, a building with 22 floors above the ground and 5 floors underground is built. Top-down is applied as the construction method on this base and the internal strut system diaphragm supports are implemented in the form of floor slab and temporary H-beam. Owing to the large length of base and large scale of excavation, two cross walls are set to divide the base into three zones for sectional construction, as shown in Fig. 7.

In this case, observation is carried out in the B zone, results of which could serve as the research reference for retaining wall deformation and ground settlement. The measured data are compared with analysis results in order to investigate the maximum retaining wall deformation achieved from observation and the top-down analysis, respectively. According to the monitoring records of the B zone, the maximum deformation of the east side of the retaining wall is 87.75 mm (at the depth of 20.5 m) while that of west side is 107.12 mm (at the depth of 22.5 m), where the maximum ground settlement is 165.3 mm.

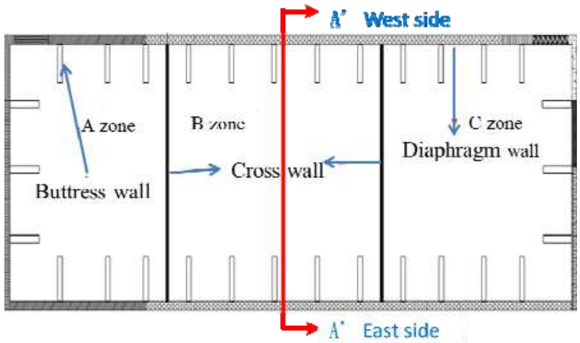

Fig. 7: Construction plan of retaining wall for Case I

Data measured by the inclinometer on the west side are taken as the comparison criteria of analysis wall deformation. Analysis results indicate that the wall deformation in this case is 107.8 mm (at the depth of 18.2 m), which is pretty close to the actual measured value, as shown in Fig. 9.

Figure 9 demonstrates the comparison of ground settlement between measured data and analysis results calculated using the normalized ground settlement curve developed by Hsieh and Ou (1998). It is known from the figure that the actual observed values are slightly larger than the predicted analytical ones.

Apart from the geological condition of ultra-soft clay stratum in the range of base excavation depth (N is equal to 2–4), this can potentially be explained by the fact that buttress wall and cross wall are not able to work efficiently due to inappropriate design and construction. Connecting end-plates should be installed between the diaphragm wall and cross/buttress wall, and these walls need to be built in one piece during construction to prevent the defects of concrete intermixed with slurry to happen on construction interfaces, which could eliminate the effectiveness of the cross wall and the buttress wall. Owing to the lack of an end plate between the retaining wall and the cross/buttress wall, there exist weak interfaces between the walls, generating a significant difference between observed and analytical values of wall deformation and ground settlement.

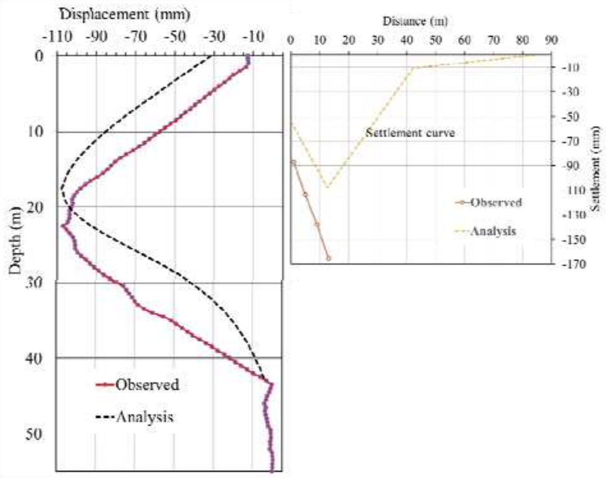

Fig. 9: Comparison of retaining wall deformation and ground settlement between analysis data and observed data in Case I

2.2 *Case II (Top-down)*

This case is investigated based on a reinforced concrete structure with 25 floors above the ground and 4 floors underground. Underground excavation depth is approximately GL.−16.6 m. The top-down construction approach is applied as the diaphragm method for excavation. The retaining wall is 100 cm thick and 39 m deep. The base is a rectangle with an area of about 8.927m^2. Moreover, 18 buttress walls and local horizontal struts are applied, as illustrated in Fig. 10.

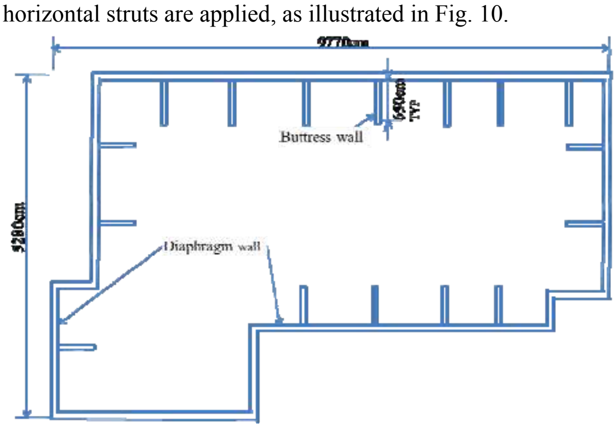

Fig. 10: Construction plan of retaining wall and buttress wall in the base of Case II

According to the monitoring records, the maximum wall deformation and the maximum ground settlement of the north retaining wall are 66.65 mm (at a depth of 15 m) and −39.5 mm, respectively. It is known from the drilling report, that the mean value of N above a depth of 30 m is approximately 3 and the corresponding stratum is soft clay. Wall deformation obtained using the RIDO is −69.95 mm (at the depth of 15 m). By comparing the analysis results with the measured data (Fig. 11), tendency of the diaphragm wall displacement in the final excavation stage can be deduced. Results indicate that the maximum deformation is roughly in agreement with the measured data.

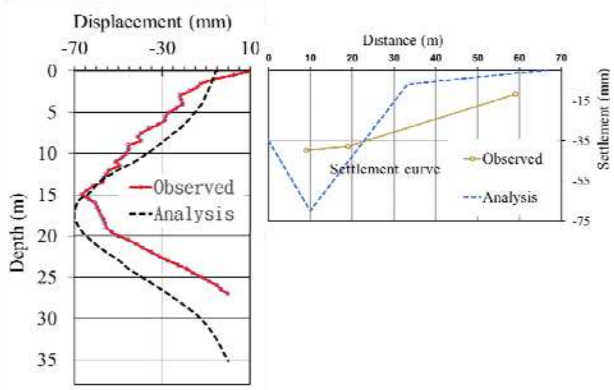

Fig. 11: Comparison of retaining wall deformation and ground settlement between analysis results and safety-observed data in Case II

2.3 *Case III (Top-down)*

This case is analyzed based on a rectangular base (Fig. 12) with an area of 7,530m^2 where a building with nine floors above the ground and five floors underground is built. A retaining wall, 120 cm wide and 43 m deep, is adopted as the diaphragm structure of excavation (excavation depth, 20.6 m). The top-down construction method is used for excavation in this case. Excavation is implemented in five stages and the basement floor slabs are gradually constructed as supports.

2.4 Comparison of wall deformation and ground settlement between analytical and observed data for case III

In this case an H buttress wall is used as the buttress measure to significantly increase the buttress stiffness efficiency. For this type of H buttress wall, if the calculation is conducted using the simplified method of general buttress analysis proposed by Hsieh and Lu (1999), where friction only in the parts of buttress wall perpendicular to the diaphragm wall is taken into account without considering passive earth pressure of the end segment of the buttress wall parallel to the diaphragm wall, computational results would become excessively conservative, leading to differences between analytical and observed data. Results indicate the efficiency of H buttress wall on wall deflection reduction. The maximum measured and analysis data of wall deflection are −39.75 mm (15 m) and −63.27 mm (19.65 m), respectively. The maximum measured ground surface settlement is −28.1 mm.

The difference between measured and analysis values exists due to the fact that constructing an H buttress wall can substantially decrease the wall deformation and using a connecting-plate can improve the combination of H buttress wall and diaphragm wall during construction. The maximum wall deformation obtained from analysis after modification was −39.3 mm (Fig. 14), which is close to the measured value of SID-7, −39.75 mm (15 m).

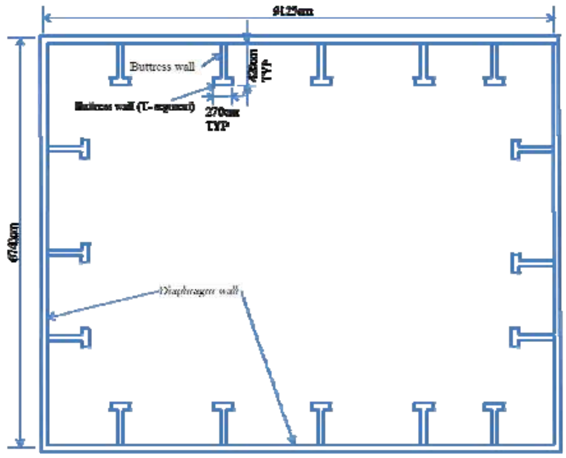

Fig. 12: Construction plan of retaining wall and buttress wall in Case III

The ground surface settlement in this case exhibits a triangular style, different from the grooved settlement in other cases. Ground settlement pattern is closely related to wall deformation. It can be seen from the retaining wall displacement curve that compared with other cases, this case has a cantilever wall displacement, which might be the reason for the triangular pattern of ground settlement of this case, different from the grooved settlement of other cases. The ground surface settlement in this case exhibits a triangular style, different from the grooved settlement in other cases. Ground settlement pattern is closely related to wall deformation. It can be observed from the comparison of analysis and measured data in the settlement curve of Fig. 14 (right) that the settlement curve estimated based on the triangular settlement is closer to the practical situation of Case III.

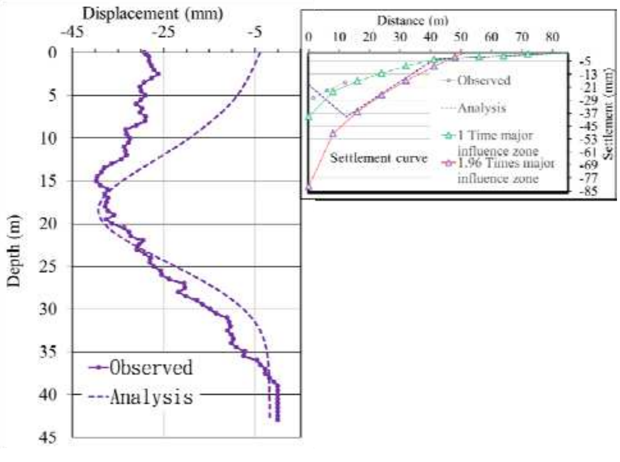

Fig. 14: Analysis value of SID-7 retaining wall deformation after modification is 39.3 mm; comparison of ground settlement between analysis data and measured data.

It can be seen from the distribution of measured data marked with blue circles in the figure that, the settlement curve estimated based on triangular settlement pattern better conforms to the practical situation for this case.

2.5 Case IV (Bottom-up)

This case is investigated based on a building with 14 floors above the ground and 2 floors underground. Retaining wall thickness, depth, and excavation depth as 60 cm, 25 m, and 11.99 m, respectively. The bottom-up construction approach with internal supports is adopted as the excavation method in this case. Three layers of supports are set up in four stages of excavation.

In order to protect adjacent buildings, an additional layer of horizontal struts is added at the depth of the second phase excavation before the upper second layer of horizontal struts are removed for basement floor construction and micro piles are used as underpinning. In the RIDO analysis, the effectiveness of micro piles underpinning is hard to simulate. The values of the measured data of wall deformation (18.58 mm at a depth of 12.5 m in SID-3) and ground settlement (20 mm on SM-9) are both lower than the analysis results (28.4 mm wall deformation at a depth of 12.5 m and settlement of 2 mm), as demonstrated in Fig. 16.

2.6 *Case V (Bottom-up)*

The base in this case has an area of 6,643m^2 , on which a school building with four floors above ground, three floors underground, and an underground parking lot are built. An 80-cm-thick retaining wall is erected as the diaphragm structure with a depth of 33.8 m. The excavation depth is 15.2 m. The bottom-up construction approach with internal struts is used in this case.

At the end of the last excavation stage in this case, deformation of the east of the wall is 74.48 mm (at a depth of 14.5 m). During the process of removing the third layer of support, analyzed deformation is 78.1 mm (13.25 m). The maximum deformation roughly coincides with the analysis result in Fig. 17.

2.7 *Case VI (Bottom-up)*

In this case, a building with 15 floors above the ground and 4 floors underground, whose base area and underground excavation depth are 8,180 m^2 and 21.8 m, respectively, is investigated. The bottom-up construction method with internal supports of retaining wall is used as the diaphragm measure of the excavation. The retaining wall is 120 cm thick and 38 m deep with a six-layer internal support system. The maximum observed retaining wall deformation is 42.08 mm (in SIS-2 at the depth of 23.5 m) and the maximum ground surface settlement is 22.3 mm in this case. The maximum wall deformation achieved from numerical analysis using RIDO is 46.546 mm (at the depth of 15.9 m). Detailed results are shown in Fig. 18.

3 COMPREHENSIVE DISCUSSION OF THE EFFECTS OF THE EXCAVATION METHODS

3.1 *Discussion of diaphragm wall deformation*

Based on the six cases introduced above, relationship between the maximum diaphragm wall deformation (represented by the vertical axis) and the excavation depth (represented by the horizontal axis) is established in Fig. 19. This figure demonstrates that the ratio of the maximum wall deformation to the excavation depth in the top-down cases is within 0.2%–0.5%, while ratio in the bottom-up cases is in the range of 0.16%–0.5%. It seems not obvious in effects of difference between the top-down and the bottom-up construction methods on the ratio of the maximum wall deformation to the excavation depth as observed from this figure. However, in the three bottom-up cases, only case VI uses a buttress wall for construction. For these three cases, deformation of case V is fairly large while deformation values of other two cases are all concentrated in the lower range. Even with a buttress wall and a cross wall, wall deformation in top-down cases shows no significant decrease. Therefore, it can be inferred that wall deformation in top-down excavation is likely to be larger than that of bottom-up excavation. This might be caused by the fact that there is no long-time standing during the bottom-up excavation processes, preventing a significant influence of creep on the wall deformation. Therefore, the the ratio of the maximum wall deformation to the excavation depth shows a little smaller than that of top-down excavation method.

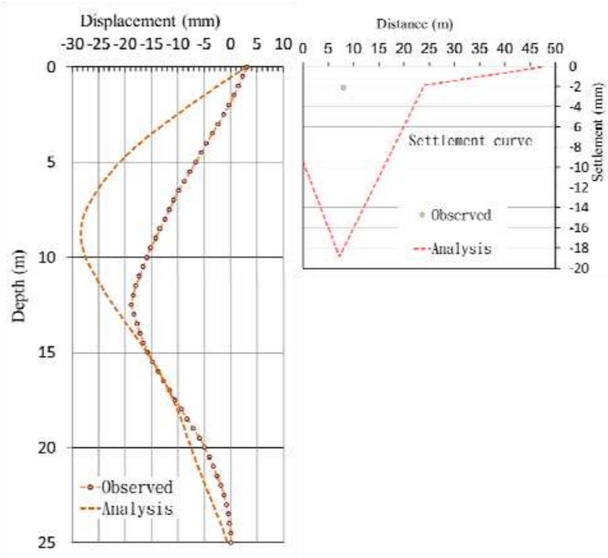

Fig. 16: Comparison of retaining wall deformation and ground settlement between measured and analysis data in Case IV

Among all the major factors that influence wall deformation, the soil parameter has a fairly noticeable effect on the numerical analysis due to substantial variations of the undrained shear strength of clay, Su, and passive earth pressure coefficient of sandy soil, Kp. It is known from the comparison of wall deformation between the observed and the analysis data and within the upper and lower limits, δhm = (0.2%–0.5%) He, proposed by Ou et al. (1993) shown in Fig. 19 that, ratio of δhm to He is within 0.2%–0.5% in three top-down cases. In these three cases, Case III presents the smallest wall deformation under the action of an H buttress wall. This can be explained by the fact that the wall deformation can be efficiently reduced using an H buttress wall as designed, and a superior connection between the H buttress wall and the retaining wall can be generated using a connecting plate in construction. However, owing to the difficulty to directly simulate H buttress wall in RIDO, there exists a certain difference between the analysis and observed data. The difference is within 0.2%–0.5% in one of the three bottom-up cases and under 0.2% (out of the range 0.2

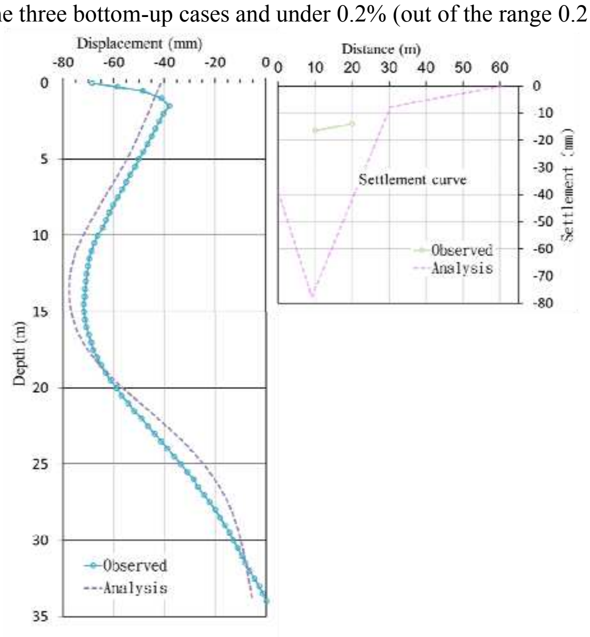

Fig. 17: Comparison of retaining wall deformation and ground settlement between analysis and safety-measured data in Case V

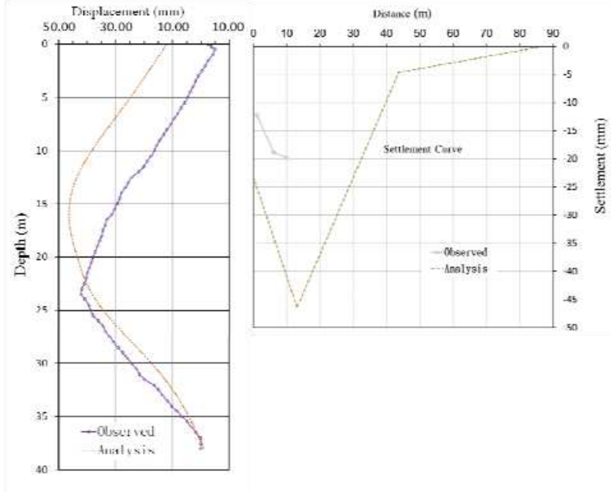

Fig. 18: Comparison of retaining wall deformation and ground settlement between observed and analysis data in Case VI

%–0.5%) in the other two cases. Wall deformation is fairly low in Case IV because of the small scale of the excavation zone and the measures to protect the base from adjacent buildings. Case VI has the deepest excavation (21.8 m) among all the cases. Although the geology above the excavation face in this case is soft clay, where N value averages between 2–3, this case is the only one that utilizes the 400*400*13*21 B4F steel strut in the basement design, allocates excavation in seven layers, and sets up six layers of supports. The maximum wall deformation for this case is 47.28 mm.

Figure 19 illustrates the average creep rate in the standing stages of construction in the three top-down cases. The maximum average creep rate of Case I is approximately 0.41 mm/day, while Case III possesses the minimum average creep rate, at 0.11 mm/day. Therefore, Case I has the maximal lateral deformation and Case III has the minimal lateral deformation. However, considering that the application of floor slab as supports could increase the factor of safety and the simultaneous construction above and under the ground could save construction time, top-down is also frequently adopted for deep excavation.

3.2 *Discussion of ground settlement*

With the vertical axis representing ground settlement and the horizontal axis representing the excavation depth, Figure 20 demonstrates that the ratio of maximal ground settlement to maximal diaphragm wall deformation in top-down construction is roughly 0.19–0.78, while the ratio in bottom-up construction is approximately 0.15–0.49. Top-down cases essentially have extremely large ground settlement under the action of disturbance. For other top-down cases, in the areas primarily consisting of clay, excavation wall deformation would be relatively high in theory due to the standing creep. In this

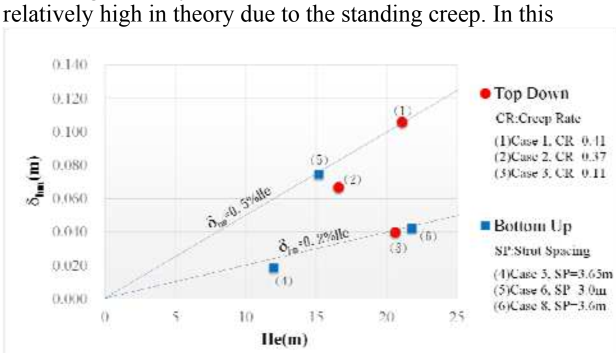

Fig. 19: Relationship between the maximum lateral deformation of diaphragm wall and the excavation depth

manner, ground settlement of top-down is supposed to be larger than of that of bottom-up.

This investigation indicates that the maximum ground settlement of deep-excavation site in softy soil of the Taipei Basin is also under 0.5% of the excavation depth. Only Case I has a maximum ground settlement larger than 0.5% of the excavation depth. This is potentially due to the excessive disturbance to the soil behind the diaphragm wall in construction, which leads to the fact that soil strength or deformation might not have been recovered when basement excavation commences. Another reason is the soil plastic flow. Based on the retaining wall lateral deformation of base excavation, under the premise of the presence of fairly limited soil behind the diaphragm wall, more ground settlement would happen for filling the space generated by the lateral deformation of the retaining wall, making a maximal ground settlement higher than 15 cm, which reaches 1.5–2.0 of the empirically estimated value. That is, the settlement value dramatically exceeds the generally suggested empirical value 0.5% δ_{hm} (Ou and Chang, 2002). Disturbance effect is caused by the successive excavation on the two sides of the base, which repeatedly impacts the soil and thereby causes a ground settlement larger than normal value.

3.3 *Relationship between retaining wall deflection and ground settlement*

In order to study the relationship of diaphragm wall deformation and ground settlement generated using top-down and bottom-up in the six cases, Figure 24 of upper and lower limits is drawn according to the relationship developed by Ou and Chang(2002) with the vertical axis representing the ground

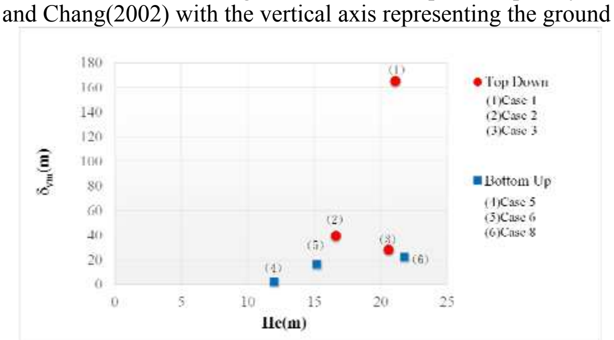

Fig. 20: Relationship between the maximum ground settlement and the excavation

settlement and the horizontal axis representing the diaphragm wall deformation. It can be seen that with reference to the top-down construction method, the top-down cases investigated in this work are all implemented on bases mainly composed of clay. However, relationship between ground settlement and wall deformation of top-down cases, marked with red indicators in Fig. 24, is more like the situation with sandy stratum whose ratio is relatively low (the large ratio in Case I might be caused by disturbance). This might be so because the cases collected by Ou and Chang(2002) are those without buttress wall or cross wall while top-down cases in this work are all equipped with buttress wall or cross wall. Therefore, this result is likely to be affected by the reduction effect of buttress wall or cross wall on ground settlement and wall deformation. For bottom-up, there are two points on the lower limit, 0.5δhm, one point on the upper limit, δvm=δhm, and one at the median, 0.75δhm, indicating that top-down method and bottom-up method have different effects on wall deformation and ground settlement. It can be observed that excavation depths of top-down cases are all around 20 m while those of bottom-up cases are approximately 15 m. As ground settlement and wall deformation are interrelated, the maximum ground settlement needs to be estimated from the maximum wall deformation of excavation according to the relationship between them. Comprehensive results show that wall deformation and ground settlement of the top-down method are higher than those of the bottom-up method.

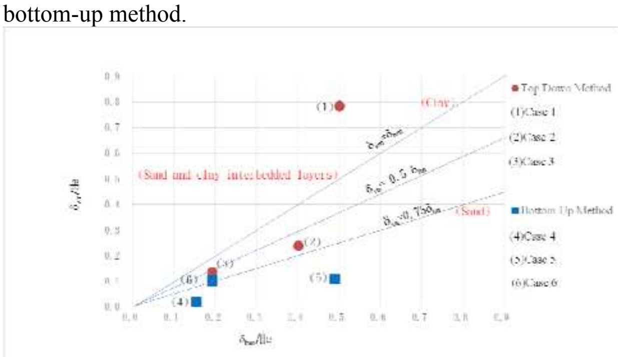

Fig. 24: Relationship between the maximum diaphragm wall deformation and the maximum ground settlement

It is known from Table 3 that the standing time of top-down in each stage, from excavation completion to reinforced concrete (RC) maintenance of floor slab, is relatively long, averaging to approximately 20–60 days. Excavation of the next stage is applied when the RC has a sufficiently large strength after construction and maintenance. Generally, the diaphragm wall deformation caused by standing time would increase with the standing time, which is the creep property of top-down construction method. According to creep rate in standing time of three top-down cases, mean creep rate generated by standing time is 0.41 mm/day in Case I, 0.37 mm/day in Case II, 0.11 mm/day in Case III.

4 CONCLUSIONS AND SUGGESTIONS

1) When the buttress wall and cross wall are used without the connecting plate for combination and eliminating defects of concrete intermixed with slurry generated at joints, the actual effectiveness of the buttress wall would be reduced.

2) An H buttress wall has a superior effect on restraining diaphragm wall lateral displacement.

3) A fairly long standing time is required in each stage from excavation completion to RC maintenance of floor slab for deep excavation using the top-down construction method. Research indicates that diaphragm wall deformation and ground settlement are both closely related to the creep caused by the standing time. Therefore, time effect should be taken into consideration in the top-down excavation analysis.

4) The maximum wall deformation of deep excavation in the Taipei Basin area is in the range of 0.5–0.75 δ_{hm}, with sandy soil at the lower limit, clayey soil at the upper limit, and sandy and clayey soil interbedded layer within the range. However, for soft clay, the maximal wall deformation might exceed two times of the maximal ground settlement.

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