Geotechnical Aspects of Underground Construction in Soft Ground – Viggiani (ed)
© 2012 Taylor & Francis Group, London, ISBN 978-0-415-68367-8

Effect of staged dewatering and excavation on the heave of soil beneath deep excavation

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ABSTRACT: Deep excavation in soft ground can induce significant heave of soil beneath the bottom of excavation. Field measurement of a staged excavation project using top-down method was carried and shown that vertical displacement of uplift pile supporting permanent column is large. For staged dewatering and excavation, dewatering at each stage can increase the relief of effective stress of each stage of excavation compared with staged excavation without dewatering, so the effect of staged dewatering on the behavior of soil need to be investigated. Triaxial tests were performed to simulate the process of staged dewatering and staged excavation. Test results show that dewatering can reduce the final amount of heave of bottom of excavation. Soil located at different location relative to the excavation is subjected to different stress path. This leads to that larger heave of bottom of excavation close to diaphragm wall compared with that close to center of excavation. The effect of dewatering must be taken into account when predicting heave induced by deep excavation in soft ground.

1 INTRODUCTION

Dewatering is necessary to lower the ground water table below bottom of deep excavation in soft ground. For deep excavation using bottom-up method, multi-level struts or slabs are needed to maintain the stability and to reduce the internal forces and deformation of diaphragm wall. In such case, the whole construction activities include staged dewatering and excavation. At each stage, dewatering is first performed to lower the ground water table down to 0.5 m~1 m below the bottom of the following subsequent stage of excavation, then the soil to be excavated at the subsequent stage of excavation is removed. Step by step, the subsequent staged dewatering and excavation can commence until the final bottom of excavation is reached.

Deep excavation in soft ground can induce significant heave of bottom of excavation and consequently cause vertical displacement of pile supporting permanent column and sometimes diaphragm wall when top-down method is employed. Furthermore, heave of soil beneath bottom of excavation can induce tensile force in pile. The uneven upward displacement between piles and that between piles and diaphragm wall can induce additional internal force in the slabs and columns. Besides, when there is existing tunnel located under the excavation, the heave of soil can cause the upward movement of tunnel. Thus, the effect of soil heave on the underground structures must be limited to prevent causing any damage to underground structure, or negative effect on the serviceability of underground structure.

The heave of the bottom of excavation has long being paid attention to since 1950s. Stanley (1956) reported that large heave of bottom of excavation can occur for deep excavation without dewatering, however, the heave of excavation bottom can be greatly reduced by dewatering before excavation commence. Burland (1979) has investigated soil movements around excavations in London clay. Buford (1988) reported the heave of tunnels beneath an excavation in London due to the heave of overlying soil. The maximum heave measured was about 20–30 mm after excavation activities in 1957 and this upward displacement still continued and maximum magnitude reached about 50 mm in 1986. Lo & Ramsay (1991) proposed the methodology to deal with the "construction over tunnels" problem by a case record of excavation above subway tunnels in Toronto. Zheng et al. (2010) carried centrifuge tests to investigate the effect of overlying on tunnel linings.

The heave of soil beneath the bottom of excavation can induce the upward movement of pile. Consequently, tension force is generated in the pile body (Iwasaki et al. 1994). The heave induced tension may be influenced by the excavation depth, pile length and soil modulus (Lee et al. 2001, Poulos & Davis 1980, Huang et al. 2007.). Zheng et al. (2010) carried centrifuge tests on the effect of deep excavation on the capacity of smooth single pile in sand and indicated that the pile's vertical capacity is reduced by up to 20%, i.e., the capacity of the pile loaded after excavation is only 80% of that of the pile loaded on the ground surface, as in a conventional loading test.

Although the heave of bottom of excavation and its effect on underground structure has been investigated and a lot of papers regarding this issue have been published, however, the behavior of soil inside the excavation during staged dewatering and excavation has not been paid much attention. This paper presents the triaxial tests and field measurements performed by the authors to investigate the effect of staged dewatering and excavation on the behavior of soil beneath the bottom of staged excavation, and on the upward displace of piles supporting permanent columns when top-down method is employed.

2 FIELD MEASUREMENTS

A deep excavation project located in Tianjin, China using top-down method was monitored. The depth of excavation is 25.8 m with 3 levels of slab, which are supported by permanent columns, as shown in Figure 1. The permanent columns are plunged 2.5 m into the piles.

The diaphragm wall is 48 m deep with 1.2 m width. The diameter of bored pile is 2.2 m and the

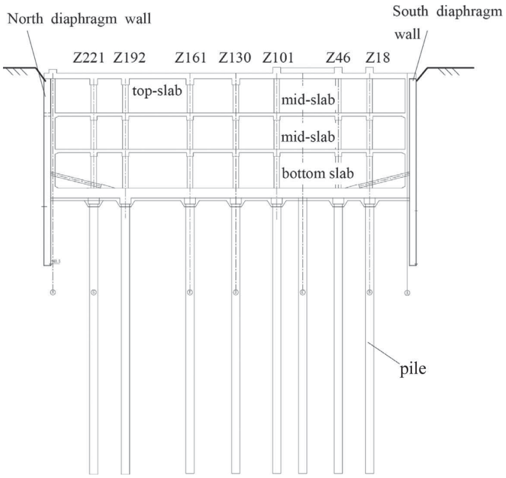

Figure 1. Profile of excavation using top-down method.

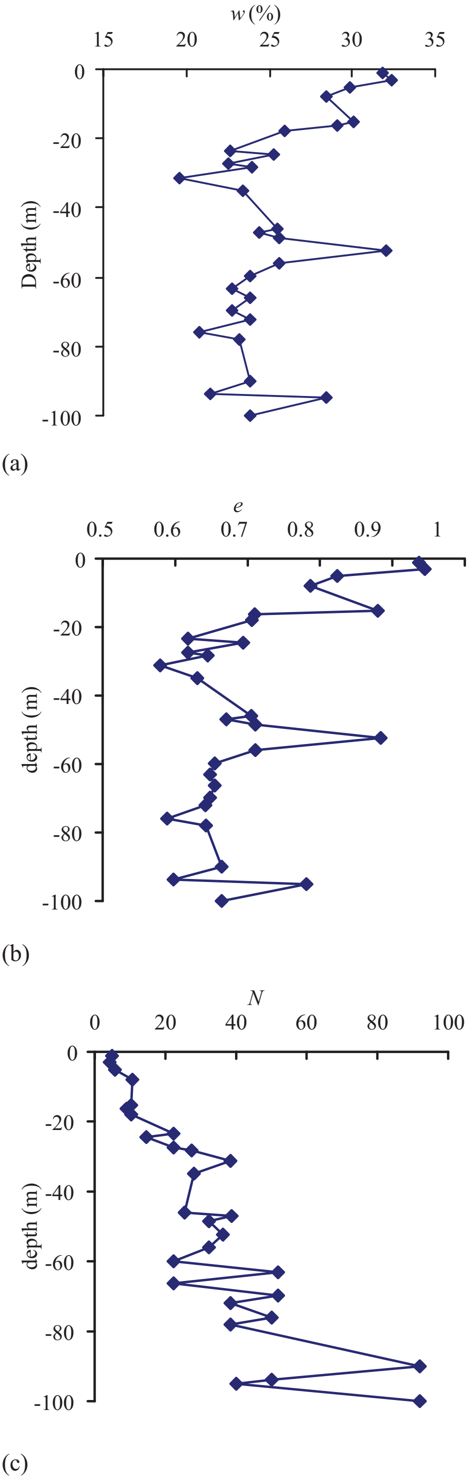

Figure 2. Soil parameters distribution along depth: (a) water content; (b) void ratio; (c) blow count of SPT.

length is 55 m. The permanent column is steel pipe. The depth of roof slab is 3 m below ground surface, the 1st mid-slab is 6.2 m below the top slab, and the 2nd mid-slab is 6.6 m below the 1st mid-slab. After the depth of 25.8 m is reached, the bottom slab is constructed and then dewatering is terminated.

The ground is mainly comprised of silty clay and silt, underlain by sand layers 80 m below ground surface. The main parameters of soil are shown in Figure 2.

Staged construction is adopted during the whole excavation process. Dewatering, excavation and construction of slab are performed subsequently at each stage. Dewatering is performed by deep wells with depth of 40 m and spacing of 15 m inside the diaphragm. The diameter of deep well is 273.6 mm.

During the staged excavation, the vertical movement of roof slab corresponding with the location of permanent columns and diaphragm wall was monitored, as shown in Figure 3. In the figure, SE denotes staged excavation and MS is mid-slab in Figure 1. The measured vertical displacement of roof slab at the locations of permanent columns can be roughly regarded as the displacement of piles if the compression of permanent columns is neglected.

It can be seen from Figure 3 that the heave of piles increased faster at the 1st stage and 2nd stage of excavation but increased much slower at the 3rd stage of excavation. That there are more loads applied to top of piles due to mid-slabs construction may be part of the reasons. However, there is one more important reason that leads to the smaller increase of heave of piles at the 3rd stage. Due to the dewatering before each stage of excavation, the ground water table was lowered from its original level, 1 m below ground surface, down to 1 m below bottom of the final excavation stage, the effective stress of soil below the lowered ground water table was increased and can thus be preloaded. Moreover, the soil beneath the bottom of excavation became over-consolidated and the degree of over consolation of soil remained became larger and larger with the further going of staged excavation.

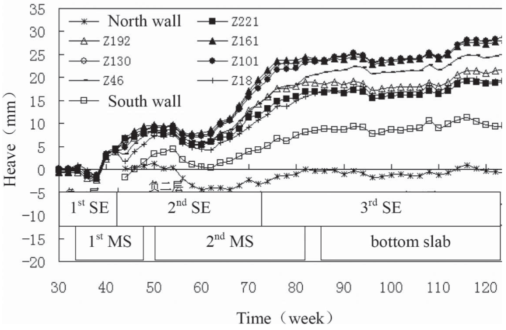

Figure 3. Heave of diaphragm wall and piles.

3 TRIAXIAL TESTS

3.1 *Stress change during staged excavation*

In order to investigate the effect of staged dewatering and excavation on the soil behavior beneath the bottom of excavation, triaxial tests were performed to simulate the stress path that the soil below the bottom of excavation was subjected to during staged dewatering and excavation. Three typical location of soil located at the bottom of final stage of excavation are considered, as shown in Figure 4. The depth of excavation is 30 m and there are totally 3 stages of excavation. When dewatering is considered, each stage of dewatering is followed by the staged excavation. The ground water table is assumed to be lowered to the same level with that of the bottom of each excavation. The process of staged dewatering and excavation is shown in Table 1.

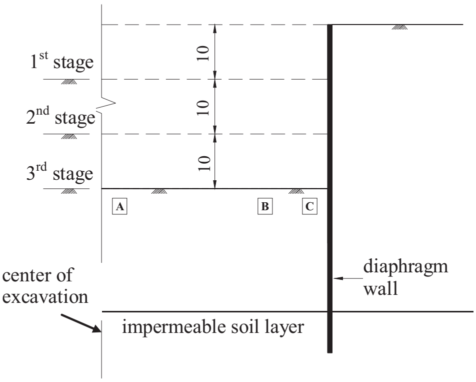

Figure 4. Schematic geometry of staged excavation (unit: m).

Table 1. Staged excavation simulation without dewatering.

Construction stages	Construction activities
Initial state	–
1st stage dewatering	Ground water table −10 m
1st stage excavation	Depth of excavation −10 m
2nd stage dewatering	Ground water table −20 m
2nd stage excavation	Depth of excavation −20 m
3rd stage dewatering	Ground water table −30 m
3rd stage excavation	Depth of excavation −30 m

In Figure 4, location A is near the excavation center line, location C is near the diaphragm wall and location B is somewhere between location A and location C. By assuming the width of excavation is infinitely large, and the process of excavation is fast enough to be regarded as undrained condition, the total vertical stress change at location A due to the staged excavation without dewatering is shown in Figure 5.

However, for deep excavation in soft ground, the soil to be excavated is subjected to staged dewatering and excavation. In this paper, the process of staged dewatering is assumed to be drained condition. If the change of unit weight of soil due to dewatering is neglected, the total vertical stress change during the whole process of staged dewatering and excavation can be easily obtained.

Similarly, by assuming the width of excavation is infinitely large, and the process of excavation is fast enough to be regarded as undrained condition, the total vertical stress change at location A due to the staged excavation with staged dewatering is shown in Figure 6a.

After the 1st stage of excavation, the soil beneath the bottom of the 1st excavation has become over-consolidated. The degree of over-consolidation of soil will increase with the further stage of excavation. Since the process of each stage of excavation is assumed to be undrained, negative pore water pressure in soil over-consolidated beneath the bottom of excavation is generated due to overlying excavation, as shown in Figure 6b.

The vertical effective stress at each stage of dewatering and excavation is shown in Figure 6c. Each stage of dewatering can increase the vertical effective stress. Consequently, the stress relief at each excavation is increased.

3.2 *Triaxial tests*

Triaxial tests were performed to simulate the stress path of soil located at the three typical locations shown in Figure 1. The soil physical characteristics are shown in Table 2.

At each stage of excavation, the soil at location A, B and C are subjected to vertical stress relief. By taking the lateral stress coefficient at rest as 0.5 and assuming that the width of excavation is infinitely large, the UU in Table 3, i.e. the ratio of

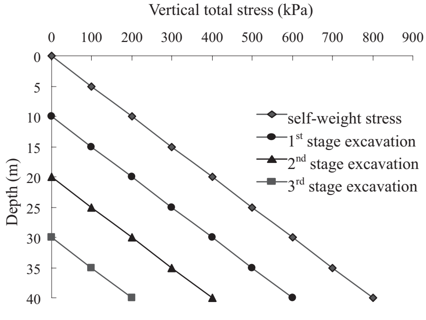

Figure 5. Changes of total vertical stress near the excavation center without dewatering.

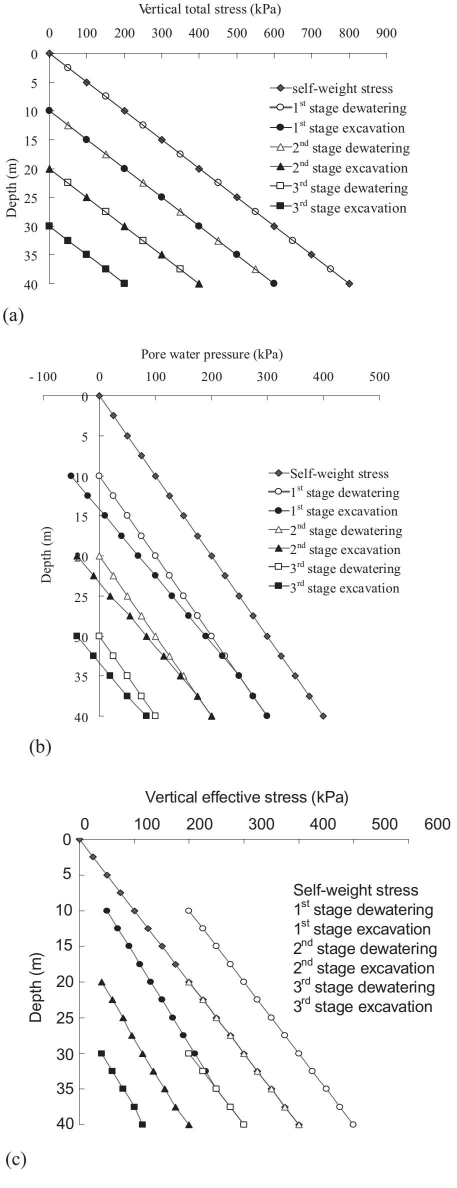

Figure 6. Stress and pore water pressure change due to overlying staged dewatering and excavation: (a) vertical total stress; (b) pore water pressure; (c) vertical effective stress.

Table 2. Physical characteristics of silty clay.

Water content w /%	Void ration e	Unit weight γ/kN/m^3	Index of plasticity I_p
25.3	0.694	20.1	12.8

Table 3. Stress paths of triaxial tests without dewatering.

	Without dewatering		
Stage	UU = 2	UU = 4	UU = ∞
1. Initial state	300/150	300/150	300/150
2. 1st stage excavation	200/100	200/125	200/150
3. 2nd stage excavation	100/50	100/100	100/150
4. 3rd stage excavation	0/0	0/75	0/150

vertical effective stress relief to horizontal effective stress relief of soil at location A can be taken as 2. While UU at location C can be taken as UU = ∞ by assuming that the horizontal stress loss due to excavation can be fully compensated by passive earth pressure. The UU of soil at location B is between that of soil at location A and location C and is simply taken as 4.

The stress path of soil specimens in triaxial tests for excavation without dewatering is shown in Table 3, the stress path of soil specimens in triaxial tests to simulate staged dewatering and excavation is shown in Table 4. In Table 3, taken UU = 2 as an example, the initial vertical effect stress at location A is 300 kPa by taking the effective unit weight of soil as 10 kN/m^3, and correspondingly, the initial horizontal effective stress at location A is 150 kPa. Thus the initial effective stress state of soil at location A can be expressed as 300/150.

3.3 *Soil behavior during excavation*

The axial strain ε_a change with the increase of major stress deviation $\Delta(\sigma_v - \sigma_h)$ for stress path shown in Table 3 is shown in Figure 7.

The relationship between axial strain ε_a and major stress deviation $\Delta(\sigma_v - \sigma_h)$ in Figure 7 can be expressed as:

$$(\sigma_{vc} - \sigma_{hc}) - (\sigma_v - \sigma_h) = \frac{\varepsilon_a}{a + b\varepsilon_a} \qquad (1)$$

where σ_{vc} and σ_{hc} are the vertical and horizontal consolidation pressure before shearing when the specimen was subjected K_0 consolation. For soil specimen subjected to triaxial tension, the vertical stress σ_v became the minor principal stress and the horizontal stress σ_h became the major principal stress. Therefore, the relationship between axial strain ε_a and major stress deviation $\Delta(\sigma_v - \sigma_h)$ was shown in Figure 8. In Figure 8, $\Delta(\sigma_v - \sigma_h)$ is normalized by $\frac{\varepsilon_a}{(\sigma_{vc} - \sigma_{hc}) - (\sigma_v - \sigma_h)} \Big/ \text{MPa}^{-}$.

Table 4. Stress paths of triaxial tests with dewatering.

	Staged excavation and dewatering		
Stage	UU = 2(*)	UU = 4(*)	UU = ∞(*)
1. Initial state	300/150	300/150	300/150
2. 1st stage dewatering	400/200	400/200	400/200
3. 1st stage excavation	200/100	200/150	200/200
4. 2nd stage dewatering	300/150	300/200	300/250
5. 2nd stage excavation	100/50	100/150	100/250
6. 3rd stage dewatering	200/100	200/250	200/300
7. 3rd stage excavation	0/0	0/200	0/300

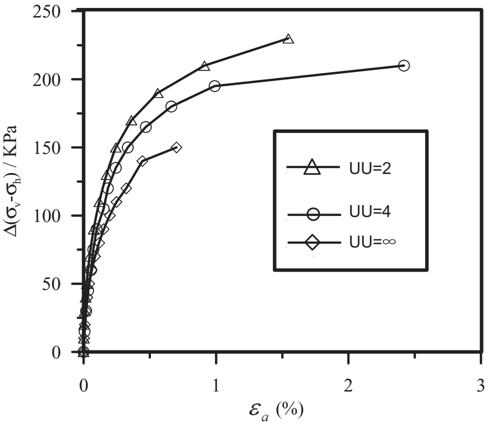

Figure 7. Stress increment-strain curves under different unloading paths without dewatering.

From Equation (1) and Figure 5 the Initial tangent unloading modulus can be obtained, as shown in Table 5.

The Initial tangent unloading modulus of soil subjected the stress path shown in Table 4 can be obtained as well by the same way, as shown in Table 6.

By comparing the initial tangent unloading modulus of soil in table 5 and table 6, it can be seen that staged dewatering can significantly reduce the

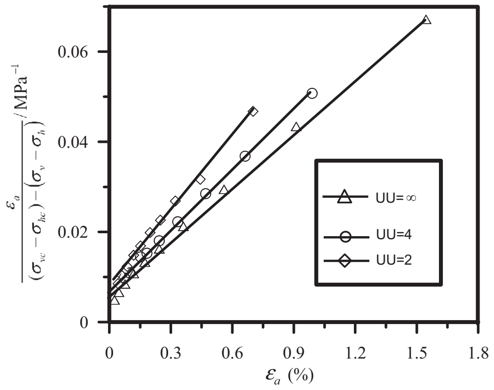

Figure 8. Hyperbolic stress-strain curve fittings under different unloading paths.

Table 5. Initial tangent unloading modulus (MPa) of soil without dewatering.

	Stress path		
Stage	UU = 2	UU = 4	UU = ∞
1st stage excavation	129.8	140.8	175.4
2nd stage excavation	50.1	57.8	52.1
3rd stage excavation	22.8	Failure	Failure

Table 6. Initial tangent unloading modulus () of soil with dewatering.

	Stress path		
Stage	UU = 2(*)	UU = 4(*)	UU = ∞(*)
1st stage excavation	212.8	312.5	400.0
2nd stage excavation	111.1	188.67	137.2
3rd stage excavation	74.6	Failure	Failure

soil compressibility and consequently reduce the heave of soil beneath the bottom of excavation.

It can also be seen from Figure 5, Table 5 and Table 6 that the soil sample experienced the stress path UU = ∞(*), i.e. the stress path of soil located at location C close to diaphragm, as shown in Figure 5, yielded the largest extension, while the soil sample experienced the stress path UU = 2(*), i.e. the stress path of soil located at A close to center line, produced the least extension. To a certain extent, this can illustrate that the heave of bottom of excavation near diaphragm wall is often larger than that near the center of excavation.

4 CONCLUSIONS

By conducting triaxial tests and field measurements, the following conclusions can be drawn:

1. Staged excavation and dewatering can induce the over-consolidation of soil beneath the bottom of excavation. The degree of over consolation of soil remained became larger and larger with the further going of staged excavation.
2. Compared with excavation without dewatering, staged dewatering can reduce the compressibility of soil below the bottom of excavation, consequently, the total amount of heave is reduced.
3. The soil located at different location relative to the excavation is subjected to different stress path. Larger heave of bottom of excavation close to diaphragm can occur compared with that close to center of excavation.
4. The effect of staged dewatering on the soil behavior can't be neglected when predicting the displacement of underground structure during excavation.

ACKNOWLEDGMENTS

This research was supported by the National Basic Research Program of China ("973 Program") (Grand no: 2010CB732106) and national Natural Science Foundation of China (Grant no. 50878144).

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