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Displacement control design method of excavation

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ABSTRACT: This paper presents a new excavation design theory-Displacement Control Design method of excavation, which is based on Time-Space Effect(TSE). Two design parameters (coefficient of active earth-pressure K_a and equivalent lateral coefficient of subgrade reaction K_h) have been discussed in details in this paper.

1 INTRODUCTION

Now there are many excavations designing methods, such as classic method, analytic method and numerical method (continuum FEM and beam system FEM, etc). The great disparity between it's assumption and reality make classic method unapplicable to design of deep excavation. Because analytic method cannot efficiently take into account the evolution of internal force of braced excavation with complex construction sequences, so it is not suitable for multi—braced excavation. Although continuum FEM is a promising design method, it has not been developed into an applicable designing method due to lack proper constitutive behavior of soil. It is known to all that a myriad of soil properties affect the magnitudes and distributions of ground movement, such as (1) Anisotropic stress—strain strength of soft clays in undrained shearing (Clough and Hansen 1981;Finno et al,1991);(2) Nonlinear stiffness properties at small shear strains(Jardine et al,1986). These complex properties can be measured in laboratory tests, but are not described reliably by the now widely used soil models (eg, linearly elastic, perfectly plastic; hyperbolic, pesudoelastic or modified Cam clay).

The conventional methods above-mentioned mainly satisfy the need of the strength and stability of excavation and usually fail to measure up to the excavation deflection demand, Moreover, they can not properly take construction sequences into consideration. Therefore, the calculated deflection and internal force always have great difference from the real deflection and internal force. In other word, existing excavation design method cannot successfully solve the environment problem around deep excavation in soft soil. Another main disadvantage of the existing excavation design method is that excavation design and construction are thoroughly separate from each other.

This paper presents a new excavation design method--- Displacement Control Design Method of excavation, which is based on Time-Space Effect (TSE).

2 THE RULE OF TIME-SPACE EFFECT

2.1 *The effect of soil rheology*

In soft clay like Shanghai, soil creep property is one of the most important engineering characteristics. Because it has great influence over ground movement around excavation and deflection of wall as well as internal force of wall, so that a series of triaxial creep test and uniaxial creep tests are conducted. These tests focus on the rheological properties of three typical kinds of Shanghai city.

Those tests shows that: the less the stress level, the smaller the creep. As the stress is less than 0.025MPa, the strain is mainly elastic.

Undrained creep is larger than drained creep by a considerable amount. When the major principal stress arrives at 0.15MPa (that is equivalent to the stress in the passive zone of an excavation with the depths of 14 or 15 meters), undrained creep develops gradually and suddenly enlarges to collapse. But at the same circumstance drained creep is waning, steady and finally converged.

When major principal stress in soil is beyond converged level, the creep develops over a limited time and accelerates abruptly to collapse soon.

The creep tests and relevant studies enlightened us to establish the following main concepts in the designing and constructing the deep excavation: (1) Layering and segmenting excavation can efficiently make use of the space effect of soil to lower the stress level and control ground movement;(2) Reducing the elapsed time in each performing step of excavation and strutting can decrease creep deformation substantially, especially significant with the elapsed time less than 24 hours.

2.2 *The space effect in excavation*

Although in the times of Terzaghi, the space effect in excavation has been broached, yet it has not been presented systematically until recently. Figure 1 is the comparison of basal heave under the different excavation length in Shanghai. From it a conclusion can be made: the longer excavation length is, the bigger basal heave and the wider the affected area. It is evident that the space effect in excavation can be used to govern the ground movement around deep excavation.

Ground movement due to excavation clearly shows that excavation is a space problem, which is closely related to soil in or around excavation. In the largest excavation of Baogang factory, due to adopting circular diaphragm wall, The magnitude of basal heave and ground movement around excavation had been dramatically reduced. Practices show that the shape, depth, size of excavation play an important role in structure deflection and ground movement.

The space effect between braced structure and soil is not only helpful to reduce the deflection and internal force of structure, but also conducive to excavation overall stability. While the research on the former is few, the later have been deeply researched in home and abroad. For example, Eide etc, on the base of thoroughly researching different shape excavation (including square, rectangle, strip), proposed equation of safety factor against basal heave. The equation is as follows:

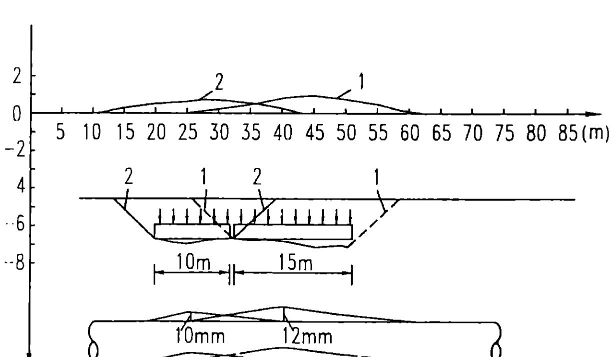

Figure 1. The comparison of basal heave under the different excavation length.

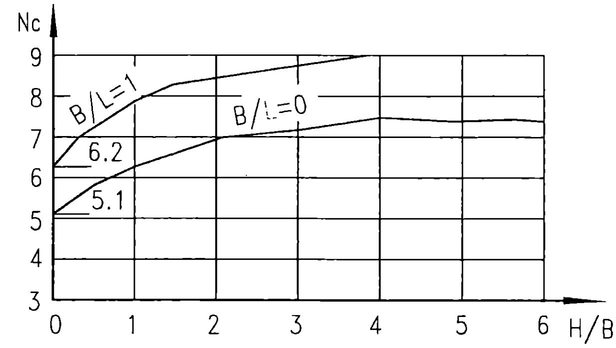

Figure 2. Variation of N_c with length, width and depth of excavation.

$$F_s = (s_u \cdot N_c)/(rH + q) \quad (1)$$

where F_s=safety factor against basal heave; s_u=undrained shear strength; γ=unit weight of soil; H=excavation depths; N_c=look up from Figure 2; q=ground surcharge.

From the equation, it is evident that F_s is directly proportional to N_c in the excavation with homogenous soil. The N_{c0} of the strip excavation (with H/B=1.0 and $B/L \to 0$) is 6.4 and the N_{c1} of the square excavation (with H/B=1.0 and B/L=1) is 7.7. Then F_{s1}/F_{s0} =1.21.

That is to say, the safety factor against basal heave of square shape excavation is about 21 percentage greater than that of stripe shape excavation. According to the above calculation, a conclusion can be made that if excavation length is equal to or less than excavation width in construction of strip excavation, safety factor against basal heave of strip excavation must increase by 20 percentage.

So it is evident that excavating by dividing the strip excavation into several short parts can greatly reduce the surface settlement and wall deflection and ground movement around excavation.

2.3 *The formation of time-space effect*

Combined the study above with lots of excavation practices during many years, an excavation construction method has been obtained. This method is to divide symmetrically and evenly soil mass into several parts through many ways such as in layers, in strips, in blocks. So that it is helpful to make most of the soil resistance in every moment to reduce the wall deflection and ground movement and to improve excavation stability.

Therefore in excavation design and excavation construction, the construction procedure with the reasonable and clear construction parameters should be designed carefully and should be put into effect. The construction parameters include the numbers of divided excavation layer, the layer thickness, the dimensions of excavated space and the elapsed time in one excavation and strutting step, etc. These construction parameters should be taken as a fundamental designing data and as the strict construction regulation in soft clay. So that the real ground movement around deep excavation can coincide with the predicted value due to the definition of the construction factor.

In general, the capacity that soil itself is potentially endue to moderate the ground movement around or in excavation should be scientifically used to solve the problems like excavation stability and deflection. Based on this conception, the Time-Space-Effect has been founded.

3 DISPLACEMENT CONTROL DESIGN METHOD OF EXCAVATION

Excavation in city always situated in area where building and lifeblood work (such as metro line) are closely concentrated. In order to ensure normal usage of the building, which are closely adjacent to excavation, the amounts of lateral wall deflection and surface settlement are limited to a certain tolerance. Sometimes the amounts of vertical wall settlement and soil lateral deflection are also limited to satisfy the stricter environment requirement.

According to environment requirement, excavations in Shanghai classify into four kinds of damage risk (shown in table 1) Therefore, excavation design should transfer from strength control into displacement control.

According to feedback calculation and theory analysis, this paper presents displacement control design method, which is based on TSE. This designing method comes from the widely used beam system FEM and has the same appearance as the beam system FEM. It inherits the advantage of beam system FEM (such as clear conception, simple calculation, fewer parameters and easily being accepted by engineer) and abandons conventional beam system FEM's disadvantages. For example, the magnitude of design parameters in conventional beam system FEM is too dependent on the designer.

Table 1. Allowable values of δ_h, δ_v and K_s for different damage risk assessments.

Risk cat.	Max. δ_h	Max. δ_v	K_s
1	1.4‰H	1‰H	≥2.2
2	3‰H	2‰H	≥2.0
3	7‰H	5‰H	≥1.5
4	7‰to10‰H	5‰to7‰H	≥1.2

*K_s safety factor against basal heave calculated by the method of circle movement.

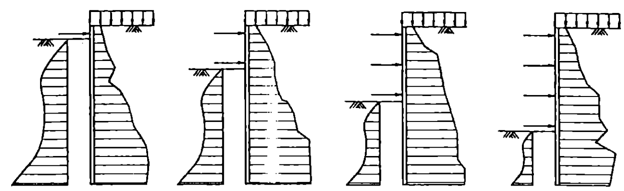

Figure 3. Dynamic computation model.

Displacement control design method is a simple and pragmatic. Although it has the same appearance as the conventional beam system FEM, the content and conception in this method are thoroughly different from conventional beam system FEM. The cornerstone of this method is rheology and it's core is TSE. The design method considers the effect of TSE on the two main design parameters (that is active earth-pressure and passive earth-pressure). This method design excavation dynamically, the active and passive earth-pressure is not a constant, but a variable. Figure 3 show the dynamic computation model. During each construction case, the active and passive earth-pressure is different.

Moreover, the magnitude of active and passive earth-pressure coefficient is dependent on time (such as nonstrutted elapsed time of one excavation and strutting step, Tr, and strutted elapsed time), space (such as nonstrutted exposed area, layer depth and layer width etc.), excavation depths and ground improvement(including dewatering), as well as soil engineering characteristic, etc.

4 DISCUSSING OF DESIGN PARAMETERS

4.1 *Coefficient of active earth-pressure*

The main factor influencing K_a is soil rheology. Different soils have different coefficients of earth pressure at rest (K_0). But K_0 of shallow clay in Shanghai doesn't fluctuate enough to have to consider it's effect. So K_0's effect has been ignored.

4.1.1 *The tendency of K_a varying with construction case*

Table2, 3 show the tendency of K_a, which vary with construction case. These K_a are measured in the excavation of Lujiazhui Metro station, Zhongyangongyuan Metro station.

From the tables some conclusion can be made:

(1) K_a in the shallower soil (above about 8 meter from ground surface) always increases during the excavation, and sometimes is greater than 1.0. This is due to compaction by heavy equipment. (2) With the exception of one or two case, K_a in the deep soil (below about 10 meters from ground surface) is less than 0.7. (3) During excavation K_a in the deeper

Table 2. Measured K_a dependent on construction case (in LuJiaZhui metro station).

DEPTH	K_0	K_a^*	CASE 1 (3.5m)	CASE 2 (6.0m)	CASE 3 (9.0m)
2.26m		0.670	0.631	0.522	0.491
5.23m	0.44	0.687	0.663	0.620	0.625
8.06m	0.44	0.730	0.699	0.632	0.621
10.96m	0.52	0.836	0.814	0.774	0.729
13.9m	0.55	0.508	0.494	0.456	0.357
15.9m	0.7	0.866	0.801	0.726	0.648
17.7m	0.7	0.649	0.635	0.597	0.517
19.7m	0.63	0.764	0.753	0.722	0.636
22.5m		0.632	0.623	0.654	0.582
25.4m		0.575	0.566	0.541	0.482

Table 3. Measured K_a dependent on construction case (in ZhongYangGongYuan metro station).

DEPTH	K_0	K_a^*	CASE 1 (3.5m)	CASE 2 (6.0m)	CASE 3 (9.0m)	CASE 4 (11.5m)
2m	0.41	0.356	0.488	0.581	0.649	0.847
6m	0.56	0.512	0.508	0.487	0.521	0.538
10m		0.486	0.474	0.456	0.461	0.475
14m	0.65	0.523	0.501	0.490	0.485	0.449
18m	0.66	0.536	0.488	0.465	0.425	0.379
22m	0.54	0.481	0.463	0.452	0.421	0.438

*Measured coefficient of active earth pressure before excavation.

soil is inversely proportional to the excavation depth, but the negative increment of different depths is different, with the maximum negative increment occurring close to the base of every excavation depth case.

The reason why K_a prior to excavation is slightly greater than K_0 is that the disturbance is caused by the installment of diaphragram, which cannot be wished in place.

K_a is closely associated with the wall deflection. With the progression of excavation depth, the deflection of wall increases and then K_a decreases. General speaking, K_a at the depth of maximum wall lateral deflection is less than the K_a at other depths, if the soil properties are the same.

4.1.2 *Time evolution of* K_a

Under a certain construction case, K_a vary from time to time. The effects of rheology on K_a are two: (1)Creep of passive area cause the increase of wall lateral deflection, which lead to the decrease of K_a in the active area. (2)Soil relaxation in active area causes the increase of K_a. When the former effect is greater than the latter's, K_a will decrease and vice versa. When the effects of the two are equal, the corresponding time is called critical time of K_a.

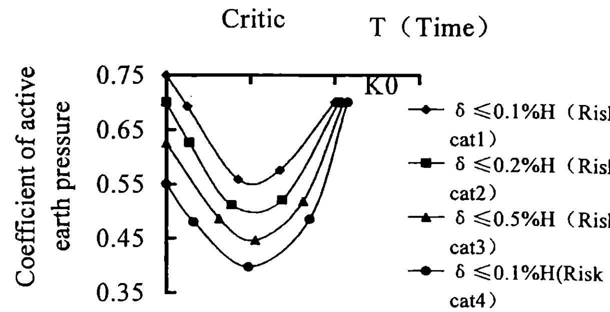

Figure 4. The relationship between K_a and damage risk.

Every depth has it's own critical time. General speaking, Critical times of most depths are at the finishing of excavation. If the time is infinitely long (such as 10 years, 20 years or even more), K_a at most depths will be near or equal to K_0.

4.1.3 *The relationship between coefficient of active earth pressure and damage risk.*

From the analysis above-mentioned, the relationships between K_a and damage risk of excavation have been established (Figure 4). The lowest point of every curve corresponds to the critic time. In a certain damage risk, the upper-limit of K_a can be used in designing when excavation is shallow, and the lowest-limit of K_a can be used when excavation is close to the base of excavation. During middle construction case, K_a are between the upper-limit and lowest-limit.

4.2 *Equivalent lateral coefficient of subgrade reaction* (K_h)

Lateral coefficient of subgrade reaction (K_h) and passive pressure are always changing in excavation due to rheology of soil and due to the difference in construction procedure. As shown in field measure, the passive earth pressures are always changing.

Therefore K_h is closely related to time, space dimension of excavation, soil parameters and reinforcement, etc. At the same time, the equivalent K_h founded on basis of TSE is closely to the construction procedure of excavation.

4.2.1 *Back-calculation of equivalent* K_h *with FEM*

Because myriad measured deflection of wall and measured active earth pressure have been accumulated in the construction of excavation, so back-analysis method can be used to search the law of lateral coefficient of subgrade reaction. The records of six inclinometer (A1—A6) and construction procedure corresponding to the six inclinometer in Orient Road Station of No.2 Metro

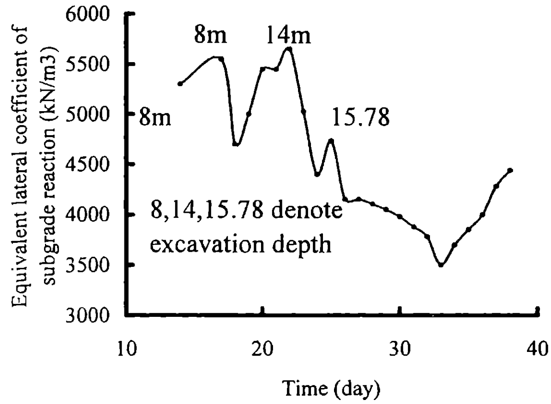

Figure 5. Variation of K_h with time and construction case at inclinometer A1.

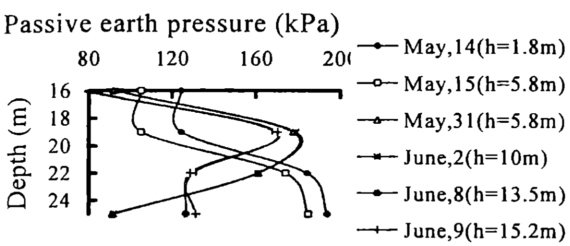

Figure 6. Variation of passive pressure with construction case of E24 section.

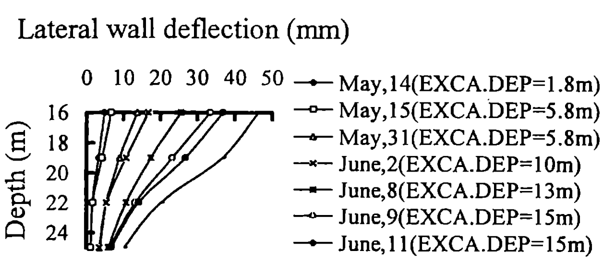

Figure 7. Lateral deflection of the wall situated on the E24 section varying with construction procedure.

line have been processed and back-analyzed with beam system FEM program. K_h is adjusted until the obtained maximum lateral deflection of wall and its position coincides with the field measurement, in a given case. Then the current K_h can be considered as the real K_h. Following is the discussion of tendency of K_h about inclinometer A1.

Inclinometer A1 is located at the end part of the whole excavation. Variation of K_h with construction case at inclinometer A1 is shown in Figure 5. Construction cases shallower than 8m are unrecorded.

The general variation of K_h at inclinometer A1 is decreasing with time. When excavation depth is at 8m below ground surface, K_h decreases from 14-th day's (the beginning time is the commencement of excavation at inclinometer A1) 5300kN/m^3 to 4700 kN/m^3. In the following 4 days from the 18-th day, K_h linearly increases with the excavation depth extending from 8m to 14m. When the excavation depth stays at 14m for 3 days, it results in the decrease of K_h from 5650 kN/m^3 to 4400 kN/m^3. During the extending of excavation depth from14m to 15.78m, K_h decreased from 4730 kN/m^3 to 3500 kN/m^3. Till mattress and base floor have been cast, K_h increases from 3500 kN/m^3 to 4600 kN/m^3 at the end part of the curve.

4.2.2 *Measured equivalent* K_h

In this section the variation of K_h was studied in another way. Earth pressure cells of standard part of Central Park Station of No.2 Metro line are placed to measure earth pressure in passive zone during construction procedure.

1)Variation of passive earth pressure with excavation procedure

Figure 6 shows the time evolution of passive earth pressure at the depth of 16m, 19m, 22m.and 25m in the passive zone. Competed data are obtained from E24 section, According to the measurement from E24, when the excavation depth is shallower than 5.8m, the relative decrease of passive resistance is larger in depth of 16m than in depth of 25m. When the excavation is 13.5m, 15.2m in height, the relative decrease of passive resistance is larger at the depth of 25m than that at depth of 16m. While in the same depth the passive earth pressure is always decreasing with the extending of excavation depth. But the passive earth pressure of 19m increase 70% on the 5th day after the excavation depth reached to 5.8m, after the 5th day, the soil pressure at this point is also decreasing. So that following conclusion can be drawn:

(1)The passive earth pressure is always decreasing due to excavation. Especially from base of excavation to 10m below the base of excavation, the decrement of passive earth pressure is more obvious because of the residual stress after unloading.

(2)In soft clay, the passive earth pressure is decreasing even the excavation depth keeps unchanged. The reason why this decrement occurs mainly is the rheology of soil. The deeper the soil and the higher the stress, then the larger the relative decrease of earth pressure is.

2)The lateral deflection of wall varying with construction procedure

Figure 7 show lateral deflection of the wall situated on the E24 section varying with construction procedure

As shown is Figure 7, The deflection of wall in depth of 16m, which is near to the base of the excavation is much larger than that in depth of 25m. On the other hand, the deflection of wall is increasing with construction procedure at every point, which is easy to understand.

3) Measured equivalent K_h

As the deflection of wall in this excavation is limited and plastic destroy could never be reached, it is reasonable that the soil deflection is always in the range of linear elasticity. Given the deflection of wall coincide with the lateral displacement of soil on the interface between soil and wall. To simplify the problem, vertical deflection is ignored. So the horizontal compression of soil could be regarded as a one-dimension problem. Of course, such simplicity may cause larger deviation at the depth of 16m or 19m than at the depth of 22m or 25m. In current problem it is still applicable. According to Hooka's law, $P_p = K_h \cdot \delta_h$, in which P_p is the measured passive pressure. The tendency of K_h calculated in this way can be drawn:

(1) With the progression of the excavation, K_h is decreasing and will be reduced more at deeper depth.

(2) Under a certain construction case, the value of K_h is decreasing with the evolution of time.

(3) Under a certain construction case and at a certain time, the value of K_h is different at different depths, K_h in the deeper area is bigger than K_h in the area near to the base of excavation.

4.2.3 *The formation of equivalent* K_h

According to the tendency of K_h and many factors (such as rheology of soft clay, space and construction procedure, etc) are taken into account, a K_h calculation model has been established.

5 CASE HISTORY

What is shown in Figure 8 is a diagram of real lateral deflection of wall in a excavation, which was not only designed according to Displacement Design method, but also was excavated according to the construction method based on the TSE. The rhelogy of soft clay was efficiently controlled. In a certain construction case, the variation ratio of maximum lateral deflection of wall is less than 0.5mm/day. After the excavation was finished, the maximum lateral deflection of wall is 29.5mm.

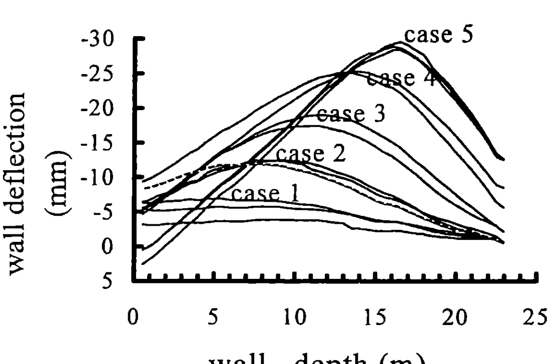

Figure 8. Lateral deflection of wall in an excavation.
Case 1: Excavation depth is 3.5m below ground surface;
Case 2: Excavation depth is 5.5m below ground surface;
Case 3: Excavation depth is 8.5m below ground surface;
Case 4: Excavation depth is 11.5m below ground surface;
Case5:Excavation depth is 14.5m below ground surface.
Excavation widths of case 1, case 2, case3, case4, case 5 are 6m, 6m,3m, 3m, 3m, respectively.

6 CONCLUSION

This paper presents a new excavation design method-Displacement Control Design Method, which is based on the Time-Space-Effect. This new design method has the similar appearance as beam system FEM, which was widely used by engineer. The deflection and internal force of wall calculated by Displacement Control Design Method is much squarer with the real deflection and real internal force than the other now-widely used design method. Moreover, this paper also emphasized that the excavation should be excavated strictly by calculated construction procedure and parameter. The Displacement Control Design Method can be used to design deep excavation in soft clay with the result of saving cost and time as well as guaranteeing the actual deflection of wall almost equal to the predicted value.

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