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Considering time-space-effect's excavation design software

G.B. Liu, Y.X. Huang & X.Y. Hou
Geotechnical Engineering Department, Tongji University, Shanghai, People's Republic of China

ABSTRACT: This paper presents a new numerical analysis software, which is based on Time-Space Effect (TSE). Design parameters of this software take time and space effects into account. At the end of this paper, a case of predicting deformation and a case of designing construction parameters are given.

1 INTRODUCTION

Finite-element analysis were first applied to braced excavation by Clough et al.(1972) and Christian and Wong(1973), and have now gained widespread acceptance through their capability to model complex construction sequences, and to incorporate detailed site-specific properties of the structural system and surrounding soils. Significant advances in these analyses have been achieved using: (1)real-time simulation of coupling between ground-water flow (pore pressures) and soil deformations, with mixed finite-element formulations; and (2)effective stress models to describe nonlinear, stress-strain-strength properties of saturated soils (under general drainage conditions). Recent case studies [e.g., Finno and Harahap(1991), Whittle et al.(1993)] have demonstrated the predicative capabilities and limitations of these numerical analyses through detailed comparisons with field monitoring data.

One of the most difficult factors to consider in the numerical analyses of braced excavations is the constitutive behavior of the soil. This is reflected in proposed design charts (Mana and Clough 1981; Clough et al. 1989), which relate wall deflections to soil properties solely through the factor of safety against basal heave. In contrast, a myriad of soil properties affect the predicted magnitudes and distributions of ground movements including: (1)Soil creep property; and (2)Anisotropic stress-strain strength of soft clays in undrained shearing (Clough and Hansen 1981; Finno et al. 1991); and (3) 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 highly simplistic soil models (e.g., linearly elastic, perfectly plastic; hyperbolic, pseudoelastic; or modified cam clay) used in most of the published analyses. Thus, most of existing excavation software cannot exactly predict wall deformation and ground deformation because of their constitutive behavior of soil failing to consider correctly above mentioned three factors.

The software discussed in this paper mainly focuses on 2-D FEM, which is not the same as the conventional one, but considers time-space effect on the soil parameters. Lateral coefficient of subgrade reaction (K_h) and active earth pressure are the two important factors in the design method. K_h is influenced by many factors, such as unstrutted elapsed time of every excavation and strutting step, layer depths and widths, unstrutted exposed area, soil condition, and ground improvement condition as well as construction case, etc. In the design of excavation, K_h used to be difficult to determine. This paper gives respectively K_h's calculation formula with relation to the factors aforementioned by back analysis of field measured data. In the meantime, the paper establishes the relationship between active earth pressure and risk catalogue of excavation. Design software, based on the established law of K_h and active earth pressure, include displacement control design software of excavation (DCDS) and ground movement prediction software (GMPS) as well as construction parameters design software (CPDS). Ground movement has been accurately predicted by GMPS in scores of deep excavations in Shanghai and the degree of accuracy arrives at millimeter grade. The CPDS has been successfully applied to design construction parameters according to the environmental demand around excavation and risk catalogue of excavation. As additional field measured records become available, these data can be readily used for further improvement on earth pressure.

2 EFFECT OF TIME AND SPACE

During long periods of practice of excavation engineering, we have introduced time-space theory and corresponding construction and calculation methods. The considering time-space-effect's excavation design software in excavation is based on time-space design theory in which time and space are two major influential factors. The following case will give a brief illustration.

The shallow soil in maritime cities in China is generally soft-plastic or fluid-plastic clay with obvious rheological characteristic. The diaphragm wall of Shanghai Qihuo Mansion's deep excavation is embedded in soft clay. According to field measurement, it is shown in Figure 1 that during excavation, deformation of diaphragm wall under the same construction case will increase correspondingly with unstrutted elapsed time of diaphragm wall.

Although excavation is shallow , soil's stress level is relatively low and construction case lasts for only four or five days, increment displacement of the wall increases obviously. This means that soft clay has rheological property, which is displayed here through the influence of time on wall deformation. The space effect on the deformation of diaphragm wall is exhibited through excavation depth and width. Under equal excavation depth, the greater the excavation width, the greater the wall's deformation will be; under equal excavation width, the greater the excavation depth, the greater the wall's deformation will be.

The influence of time and space on diaphragm wall's internal stress is dependent on the degree of diaphragm wall's deformation. If soil strata in the passive zone at the bottom of the wall are hard, or lateral displacement there is relatively small as shown in Figure 2(a), it is likely that the increment of diaphragm wall's curvature will lead to the increase of its moment. If soil strata in the passive zone are made up of saturated soft clay, it is likely that with the soil at the bottom of diaphragm wall

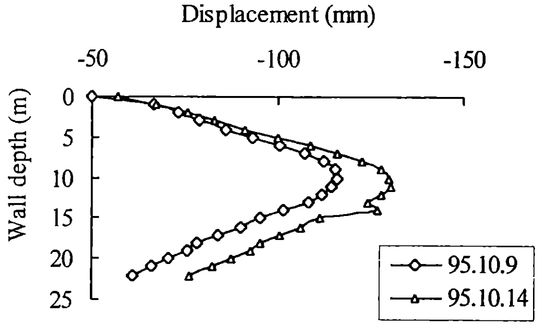
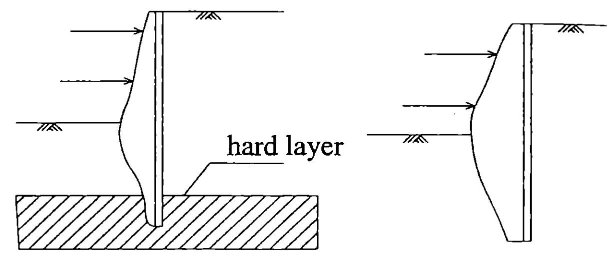


Figure 1. Diaphragm wall's deformation under certain construction case.



(a)embedded in hard layer (b)embedded in soft layer

Figure 2. The effect of soil at the toe of wall on wall deformation

moving inward, diaphragm wall's curvature will decrease, thus, internal stress will decrease correspondingly as shown in Figure 2(b). In general, rheology will increase the wall 's displacement, and its influence on internal stress is dependent on wall's curvature.

Time-space effect has an influence on bracing structure 's internal stress and deformation. This influence is mainly attributed to soil rheology, which will affect calculation parameters (active earth pressure and passive earth pressure). Therefore, in the design of bracing system, the effect of time and space should be taken into account.

However, most of the present design software for excavation overlooks the effect of time and space. Designers often make designs according to conventionally assumed case, ignoring concrete case in construction. Therefore, there are differences between design and construction. For example, random excavation construction case or random elapsed time of excavation and strutting step will cause great disagreement between designed and virtual construction case. If that happens, field measured internal stress and deformation will differ with corresponding calculated value. It is well known that a great progress is made in numerical calculation if precision can be improved by 10%. But inappropriate construction can make any perfect calculation with little or no accuracy.

One of the most notorious defects of most numerical analyses is their ignoring construction sequences and construction parameters' effects on design parameters. Another main defect of most numerical analyses is that excavation design and construction are thoroughly separate from each other.

The main feature of the considering time-space effect's design software is that there are three aspects of designed input data. The first is the support system parameters, the second is the earth (including the improved earth) parameters and the third is construction parameters. And then lateral coefficient of subgrade reaction (K_h) and active earth pressure are to be determined through these parameters.

3 LATERAL COEFFICIENT OF SUBGRADE REACTION (K_h)

Based on the back analysis of field measured data of more than ten excavations, relationships between K_h and such factors as soil strength, rheology characteristic, soil space and depth of soil stratum are generalized, and relevant formulas are established.

3.1 *Effect of soil rheology*

Figure 3 shows that soil rheology (also elapsed time of braced excavation) can influence K_h obviously. K_h will decrease sharply with the increase of time and the variation of K_h with time complys with the law of exponential function. The formula calculating the effect of soil rheology is as the following.

$$\alpha_r = \exp\left(\frac{12.0 - T_j}{T_j}\right) \tag{1}$$

where T_j——excavation time of the j-th construction case; α_r——coefficient of rheology;

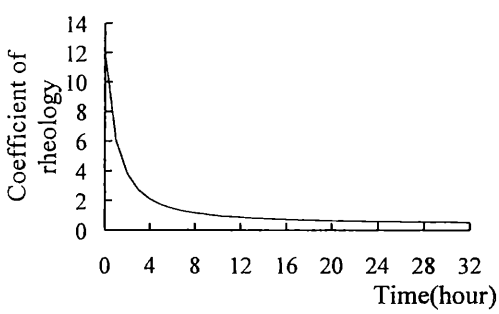


Figure 3. Effect of soil rheology on K_h.

3.2 *Effect of soil strength*

It is shown in Figure 4 and Figure 5 that K_h will increase correspondingly with the value of either φ or c. The calculating model of the effect of soil strength is as the following.

$$\alpha_c = \frac{\gamma_i(h_i - h_{i-1})\tan^2(\frac{\pi}{4} + \frac{\varphi_i}{2}) + 4c_i\tan(\frac{\pi}{4} + \frac{\varphi_i}{2})}{1.42\gamma_i(h_i - h_{i-1}) + 4.76} \tag{2}$$

where α_c—coefficient of soil strength; h_i, h_{i-1}—height of the bottom of the i-th and i-1-th.

3.3 *Effect of soil space*

Figure 6 shows the relationship between soil space and K_h. It is indicated that K_h will decrease rapidly with the increase of excavation space, complying with the law of hyperbola. Calculating model of the influence of soil space is as the following.

$$\alpha_s = \frac{1.6(h_i - h_{i-1})}{B_j} + 0.1 \tag{3}$$

where α_s——coefficient of space; h_i h_{i-1}——afore mentioned; B_j——excavation width of the j-th construction case.

3.4 *Effect of ground improvement*

It can be seen in Figure 7 that K_h will increase gradually with the increase of P_s which denotes specific penetration resistance and reflects soil's

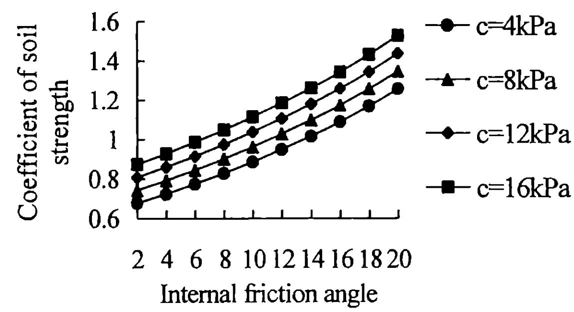


Figure 4. Effect of soil strength on K_h (h=4m).

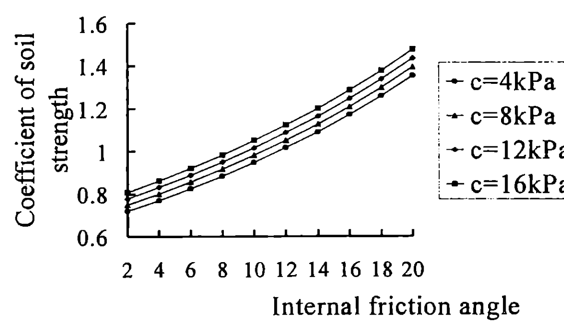


Figure 5. Effect of soil strength on K_h (h=10m).

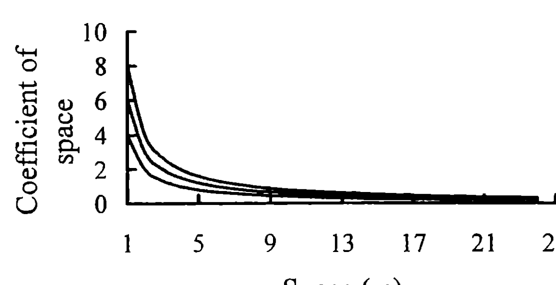


Figure 6. Effect of soil space on K_h.

strength. The effect of ground improvement can be calculated with the following formula.

$$\alpha_p = 29.34 + 1431.9p_s \tag{4}$$

where p_s——specific penetration resistance; α_p——coefficient of p_s.

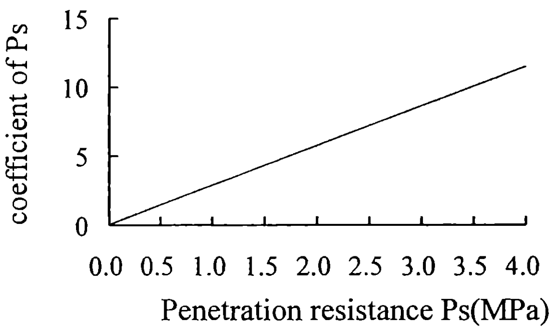


Figure 7. Effect of penetration resistance on K_h.

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

$$K_{hi} = 635 \times \alpha_r \cdot \alpha_c \cdot \alpha_s [1.0 + 0.08(\frac{h_i + h_{i-1}}{2} - H_j)] \quad (5)$$

where the meaning of the signs are mentioned before.

When the soil within excavation has been improved by some measures, K_h should be multiplied by K_{hi}. K_{hi} is as follows:

$$K_{hi} = \alpha_p \cdot \alpha_r \cdot \alpha_s [1.0 + 0.08(\frac{h_i + h_{i-1}}{2} - H_j)] \quad (6)$$

4 ACTIVE EARTH PRESURE

From summarizing many-year-practice and many – year-analysis, the relationships between K_a and damage risk of excavation have been established (Figure 8). 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 ranges between the upper-limit and the lowest-limit. In our software, K_a is determined according to the Figure.

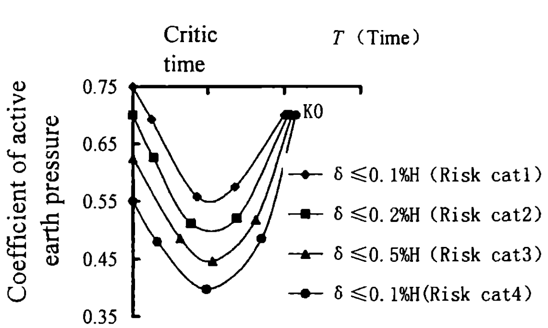


Figure 8. The relationship between K_a and damage risk

5 APPLICATION OF PROGRAM

5.1 *Tracing prediction*

Reliable predictions of wall and ground deformations are essential in the construction process for: (1)assessing the effects of excavation on adjacent facilities; and (2) identifying sections where special remedial construction measures (e.g., underpinning, ground improvement, etc.) are required. In the east part of Lujiazhui metro station excavation, program GMPS is used to predict the deformation of the wall where inclinometer A8 is located. Table 1 shows soil engineering properties of the station is 600mm in thickness, 26.5m in length, the support system is steel pipe at interval 3m.

Details about construction case are listed below.

Case1: Excavation width is 6m, excavation depth is 5m below ground surface; Case2: Excavation width is 6m, excavation depth is 8m below ground surface; Case 3: Excavation widths is 6m, excavation depth is 10m below ground surface; Case 4: Excavation widths is12m, excavation depth is 12m below ground surface; Case 5: Excavation widths is 12m, excavation depth is 15m below ground surface. Figure 9 show the recorded construction procedure at inclinometer A8.

Table 2 is the comparison of maximum lateral wall deflection between field measurement and calculation at inclinometer A8. The difference between the calculated and the measured is negligible.

5.2 *Designing construction parameters*

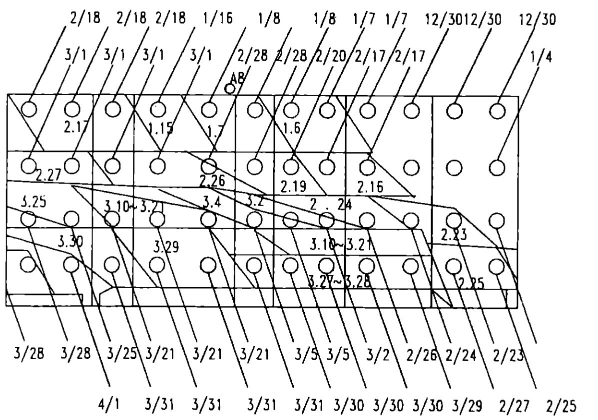
Construction of the west part of station Lujiazui is of great difficulty with the shortest distance between

Table 1. Soil engineering properties of Central Park Station of No.2 Metro line.

	Soil name	Soil thickness	Water content	I_L	Shear strength index	
		(m)	w%		c(kPa)	φ
①$_1$	Fill	1.5~3.0				
①$_2$	Fill	3.4~4.0				
②$_1$	Yellow-dark brown silt	0~2.1	31.4	0.78	14.0	17.5
②$_2$	Greyish sandy clay	2.2~7.5	34.1		9.3	16.9
③	Greyish soft silty clay	0~3.0	40.5	1.19	15.0	13.5
③$_1$	Greyish sandy clay	0~0.5	35.3		9.0	18.0
④	Greyish soft clay	6.0~9.5	52	1.31	12.8	7.8
⑤$_{1-1}$	Greyish clay	3.0~8.5	39.8	0.92	12.0	9.3
⑤$_{1-2}$	Greyish silty clay	0.0~16.0	32.6	0.81	12.9	14.2
⑤$_{1-2a}$	Greyish clay	0~4.5	34.7	0.70	12.0	11.5
⑥$_1$	Dark green silty clay	2.3~5.0	22.1	0.28	24.3	20.3

Table 2. Comparison of maximum horizontal wall deflection between field measurement and calculation at inclinometer A8.

	Case1	Case2	Case3	Case4	Case5
Calculated (mm)	16.0	60.6	88.7	102.9	110.5
Measured (mm)	10.3	56.2	86.5	95.3	105.7



Notes: "O"represent support system..
"1.7"denotes Jan. 7 when the subsection is excavated.
"1/8"denotes Jan. 8 when the support is installed.

Figure 9. Recorded construction procedure at inclinometer A8.

tunnel and excavation only 11m. In addition, an equipment house of the tunnel is only 0.2m away from the excavation of the metro station. Based on the environment protection requirements of the west part, construction parameters have been designed with the help of CDPS program. Results are show in the Figure 10. The long rectangular excavation is divided into sections with a length around 24m. In every section the excavation is also divided into certain layers based on the strut levels. Every layer is still segmented into subsections with a length less than 6m. The elapsed time in every subsection excavation is confined in a certain time limitation.

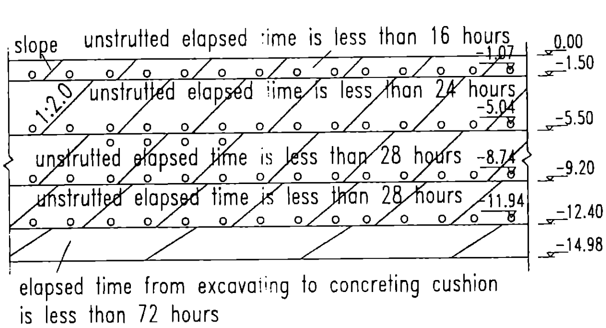


Figure 10. Construction parameter designed by CDPS program

The excavation height for the last time is 2.5m. It is required that after a half of the total width of the section(about 24m) is excavated, soil should be cleared and concrete cushion should be cast as soon as possible. The total time from the beginning of excavation to the completion of concrete cushion must not exceed 72 hours. Grade of concrete used must not lower than C20 and thickness of the cushion must be greater than 20cm. It is also required that cushion closely cling to diaphragm wall with no interruption. To speed up condensing of concrete and improve concrete's strength in early stage, add mixture can be mixed up into the concrete.

When the west part of the metro station is finished according to designed construction parameters, ground movements around the excavation satisfy the strict environment requirement. The maximum lateral wall deflection and maximum surface settlement are 20mm and 15mm respectively.

6 CONCLUSION

The considering time-space effect's excavation design software has been widely used in the analysis of excavation for more than three years. The degree of accuracy of predicating wall deflection arrives at millimeter grade. The main feature of this software is that the excavation design and construction are organically combined. In excavation design, the effect of time and space on the design parameters (K_h and K_a) has been properly taken into account. Moreover, once the construction parameters have been designed, excavation should be strictly conform to calculated parameters.

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