Discussion on the method of determining initial soil reaction force and horizontal reaction coefficient of foundation soil in passive area for foundation pit excavation

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ABSTRACT

The calculation of initial soil reaction force and horizontal reaction coefficient should consider the influence of excavation unloading on the mechanical properties of foundation soil in passive zone. This paper describes the problems with conventional calculation methods. Combining with the geotechnical test and the measured results, the calculation formula of the initial soil reaction force is derived. It is suggested that the secant modulus under the unloading stress path is used as the horizontal reaction force coefficient of the passive soil. It is hoped that it can guide the design of the retaining structure.

Keywords: initial soil reaction force; horizontal reaction coefficient; over consolidated soils; unload; secant modulus; Stress path

1 INTRODUCTION

At present, the design of the foundation pit excavation retaining structure adopts the elastic foundation beam plate method, which can better balance the coordinated deformation of the structure and the foundation soil. However, the horizontal reaction coefficient is calculated based on the empirical formula, and the calculated parameters are also the results of conventional mechanical tests under loading conditions. This method does not consider the influence of excavation unloading on the mechanical properties of the foundation soil in the passive zone, which leads to a lower degree of compliance between the calculated values and the measured results.

Considering the unloading path and consolidation state of the foundation soil in the passive area of foundation pit excavation, and analyzing the geotechnical test and field test results, this paper discusses the reasonable value method of initial soil reaction force and horizontal reaction coefficient. Finally, it is hoped to provide a basis for the design of the retaining structure of the foundation pit.

2 CURRENT CALCULATION METHOD OF SOIL REACTION FORCE AND HORIZONTAL REACTION COEFFICIENT

Taking the most popular and standardized empirical formula method as an example, this paper describes the problems with conventional calculation method for the soil reaction force and horizontal reaction coefficient. Calculational diagram is shown in the figure 1.

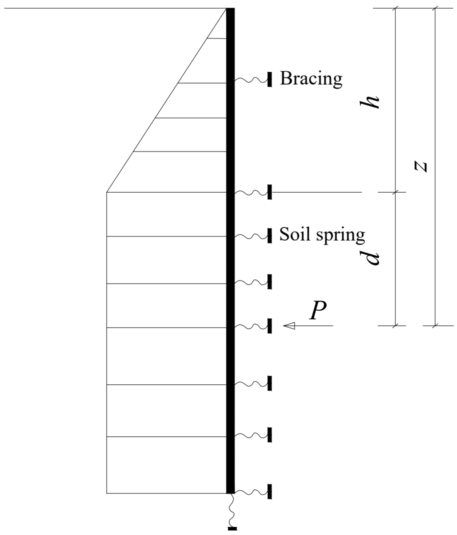


Fig. 1. Calculational diagram.

Distributed soil reaction force acting on the retaining structure:

$$p_s = k_s \cdot v + p_{s0} \tag{1}$$

Initial soil reaction force:

$$p_{s0} = \sigma_{pk} \cdot K_{a,i} \tag{2}$$

Horizontal reaction coefficient:

$$k_s = m \cdot (z - h) \tag{3}$$

The proportional coefficient of the horizontal reaction coefficient:

$$m = \frac{0.2\varphi^2 - \varphi + c}{v_b} \tag{4}$$

Among them, $K_{a,i} = \tan\left(45^0 - \frac{\varphi}{2}\right)^2$.

v--horizontal displacement value of soil compression at the calculation point.

v_b--horizontal displacement of the retaining structure at the bottom of the pit.

z--the distance from the top of the pit at the calculation point.

h--depth of foundation pit excavation.

c and φ--the cohesion and internal friction of the soil.

The calculation of the initial distribution soil reaction force and the horizontal reaction coefficient is still based on the parameters and empirical formulas obtained from the conventional mechanical tests of the loaded state. It does not consider the change of the mechanical properties and deformation characteristics of the foundation soil in the passive zone， which is caused by the foundation pit excavation unloading.

3 STRESS STATE OF FOUNDATION SOIL IN PASSIVE ZONE AFTER FOUNDATION PIT EXCAVATION

The design of the retaining structure of the foundation pit is not the limit state design, and most of the designs are mainly based on deformation control. Therefore, the ground soil in the passive zone will not reach the ultimate failure state. After the excavation of the foundation pit, the lateral pressure is reduced due to the decrease of the overburden pressure. Because of the influence of the supporting structure extrusion, the lateral pressure is reduced to a lesser extent than the latter. This paper considers the consolidation state of the soil is considered. In the triaxial test, K_0 pre-consolidation is first performed to restore its natural consolidation state, and then σ_3 is unchanged, at the same time, σ_1 is decreased. This triaxial test method is named as *“stress path method”* here.

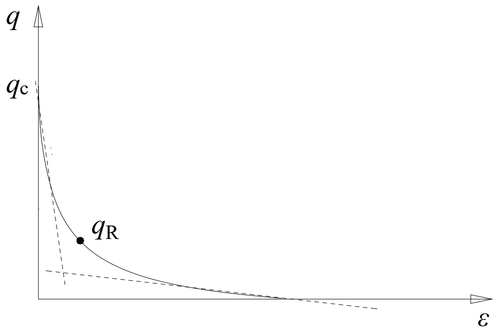


Fig. 2. Stress-strain relationship.

The author has studied the stress-strain relationship and its normalized characteristics of the soil under the stress path, but limited to the experimental conditions, σ_1 could only be reduced to the same value as σ_3. The stress-strain relationship curve under the stress path can be divided into two sections, as shown in the figure 2. The principal stress deviation at the turning point(maximum curvature K) of the two sections is recorded as q_R, and there is a large difference in modulus between the two sections. The sensitivity of the soil at different depths in the passive zone to unloading can be determined by the changes of the former and the latter sections, so that the foundation soil in the passive zone can be divided into "weakly affected area" and "strongly affected area" for foundation pit excavation, as shown in the figure 2.

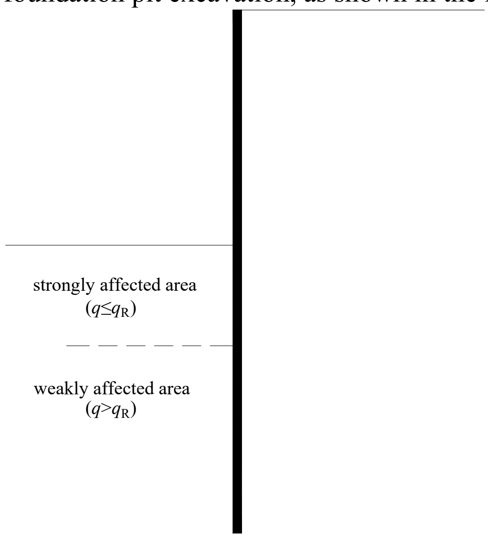


Fig. 3. "weakly affected area" and "strongly affected area".

4 DETERMINATION ON INITIAL SOIL REACTION FORCE AND HORIZONTAL REACTION COEFFICIENT

After the excavation of the foundation pit, the additional stress of the soil at the bottom of the pit can be considered:

$$p_0 = -\sum \gamma_i h_i \tag{5}$$

The unloading amount of the calculation point below the bottom of the pit:

$$p_{0,d} = \alpha_d \cdot |p_0| = \alpha_d \cdot \sum \gamma_i h_i \tag{6}$$

Among them:

γ_i and h_i--unit weight and thickness of the i-layer soil above the bottom surface of the foundation pit. If there is groundwater, use submerged unit weight.

α_d--additional stress coefficient of calculation point below the bottom of the foundation pit. The calculated depth is equal to the distance from the calculation point to the bottom of the pit.

4.1 Initial soil reaction force

Normal consolidated soil, over consolidated soil and under consolidated soil have different deformation properties and shear strength. Modern soil mechanics research has shown that the mechanical properties and deformation characteristics of foundation soil are closely related to stress history and stress state.

At the moment of excavation of the foundation pit, the foundation soil in the passive zone is still in the confined state. But to a certain degree, the overlying stress is reduced, so that it is in over consolidation state.

Lateral pressure coefficient:

$$K_{0(oc)} = K_{0(oc)} \cdot OCR^m \tag{7}$$

Over consolidation ratio:

$$OCR = \frac{\sum \gamma_j h_j}{\sum \gamma_j h_j - p_{0,d}} = \frac{\sum \gamma_j h_j}{\sum \gamma_j h_j - \alpha_d \cdot \sum \gamma_i h_i} \tag{8}$$

Initial soil reaction force:

$$p_{s0} = K_{0(oc)} \cdot \left(\sum \gamma_j h_j - p_{0,d}\right)$$
$$= K_{0(oc)} \cdot \left(\frac{\sum \gamma_j h_j}{\sum \gamma_j h_j - \alpha_d \cdot \sum \gamma_i h_i}\right)^m \cdot \left(\sum \gamma_j h_j - \alpha_d \cdot \sum \gamma_i h_i\right) \quad (9)$$

Among them:

$K_{0(OC)}$--lateral pressure coefficient of soil in passive zone after foundation pit excavation.

$K_{0(NC)}$--lateral pressure coefficient of normal consolidated soil.

OCR--over consolidation ratio.

m--empirical coefficient.

γ_j and h_j--unit weight and thickness of the j-layer soil above the calculation point. If there is groundwater, use submerged unit weight.

4.2 Horizontal reaction coefficient

The horizontal reaction coefficient is closely related to the soil modulus. In this paper, the secant modulus of soil is used as the horizontal reaction coefficient, which is intended to correlate the soil modulus with its stress state. This method makes it possible to more reasonably express the relationship between load and deformation, as shown in the figure 2.

5 INSTANCE

The instance is a full-scale test of foundation pit. The test site is cultivated land. There is no excavation and backfilling in a large depth before, and it is an undisturbed soil deposited in a natural state. The geotechnical engineering survey results show that the soil level distribution of the site is relatively uniform, and the vertical direction is obviously layered. Through the density test and high-pressure consolidation test, it is determined that the soil is normal consolidated soil.

Table 1. Physical and mechanical parameters of soil.

Layer#	Soil type	γ(kN/m^3)	K_0	c_{CU}(kPa)	φ_{CU}(°)
1	silt	20	0.33	15.3	32.1
2	silty clay	20	0.37	23.5	10.2
3	silty sand	20.5	0.33	8.3	33.2
4	clay	18.2	0.43	21.6	12.5
5	silty clay	19.2	0.37	20.7	20.1
6	silt	20.4	0.34	20.3	29.1
7	clay	18.6	0.43	31.5	14.3
8	silty clay	19.8	0.36	30.8	29.4
9	clay	18.1	0.42	29.6	19.1
10	silty clay	19.8	0.38	23.8	21.7
11	silty clay	19.2	0.40	35.6	20.7
12	silty clay	19.8	0.38	23.8	21.7

The retaining structure is cantilever row pile. The design parameters are selected from the results of the conventional triaxial test(CU test), as shown in the table 1. The calculation adopts the elastic foundation beam plate method, and the horizontal reaction coefficient is calculated by Eq. (3~4). Here, it is named as *"General Method"*. The maximum excavation depth of the foundation pit is 9m. The calculated horizontal displacement of the top of the row pile is 85.4mm, but its actual value is only 41.0mm. The foundation pit size and cantilever row pile are shown in the table 2.

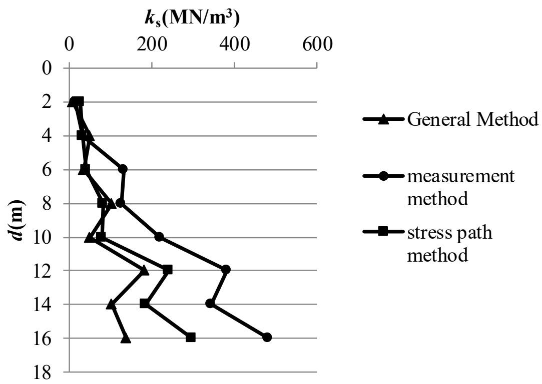
Table 2. Foundation pit size and cantilever row pile.

foundation pit size(m)			
Length:	10	Width:	6
the retaining structure			
one side:	cantilever row pile	three sides:	step-slope
cantilever row pile			
Quantity:	8	Length：	17m
Diameter：	0.8m	Pile spacing：	1.2m
Foundation pit excavation			
Step #	1	Depth:	1.5m
Step #	2	Depth:	3.5m
Step #	3	Depth:	5.5m
Step #	4	Depth:	7.5m
Step #	5	Depth:	9.0m

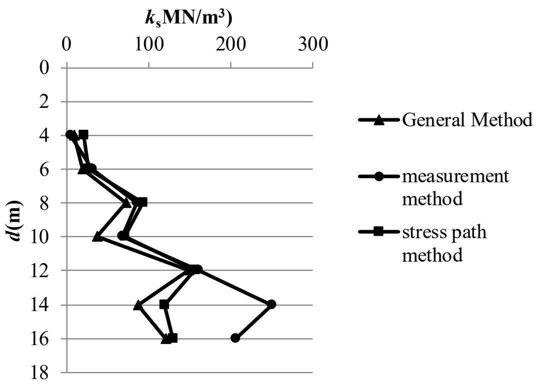
The excavation is carried out in five steps, monitoring the soil reaction force the earth pressure acting on the middle row pile and its horizontal displacement, as shown in the table 3. The initial soil reaction force is calculated by Eq. (5~9), and then the horizontal reaction coefficient can be calculated from the measured values of earth pressure and horizontal displacement. Here, it is named as *"measurement method"*, and the value of empirical coefficient (*m*) is 0.4.

The stress-strain relationship and the secant modulus are obtained by *"stress path method"*.

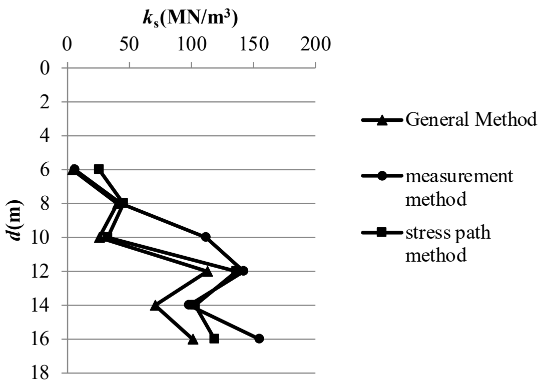
The results of the horizontal reaction coefficient of the three methods are shown in Figure 4. Overall, the calculated value of *"stress path method"* and *"measurement method"* is larger than the result of *"General Method"*, especially in "strongly affected area".



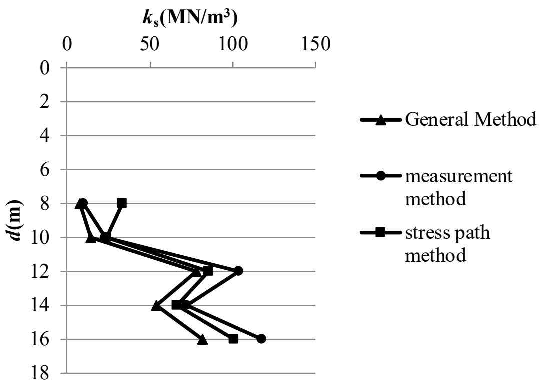
(a) step 1



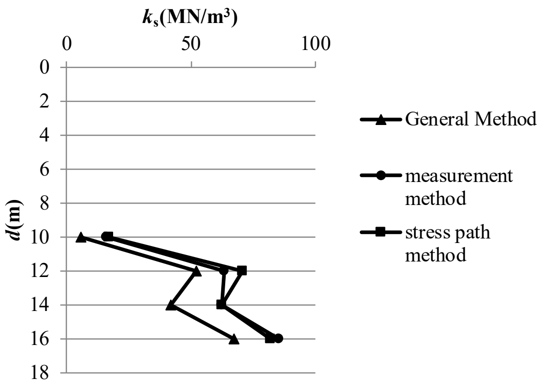
(b) step 2



(c) step 3



(d) step 4



(e) step 5

Fig. 4. k_s for each step of foundation pit excavation.

6 CONCLUSION

This paper analyzes the consolidation state and stress path of the foundation soil in the passive pit excavation, and points out the irrationality of the conventional retaining structure design method. It is considered that the design of the retaining structure should take into account the stress state of the foundation soil in the passive zone. Moreover, It deduces the calculation formula of initial soil reaction force, and discusses the method of obtaining the horizontal reaction coefficient.

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