Study on earth pressure for limited soils between main body and auxiliary structure of subway station

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Abstract. In subway engineering construction, the soil between the subway station and the auxiliary structure is considered a confined space. Therefore, it is not appropriate to calculate by Ranking and Coulomb's classical earth pressure theory. A theoretical calculation method for earth pressure on limited soils is established based on the horizontal stratified microcloud method. This method involves creating a mechanical model and taking into account the various overlying loads and bilateral contacts. It provides a reliable reference for the design of subway foundation pit supporting structures. Further analysis of parameter influence shows that increasing the width of the soil, decreasing the internal frictional angle of the soil, and increasing the interface frictional angle will result in an increase in earth pressure for confined soils. Additionally, it is observed that the width of the soil has the most significant impact on the earth pressure for confined soils. The earth pressure for limited soils is distributed in an arched shape along the depth. The earth pressure for limited soils in smaller soil action areas increases with depth.

Keywords: subway engineering; Earth pressure for limited soils; Horizontal stratified element method; Theoretical calculation method; Parameter influence analysis.

1 Introduction

With the development of urban construction, more and more cities are beginning to build subways. Subway civil engineering mainly includes the shield section, station main body, and auxiliary structures. The space between the attached structure and the main station is limited, as depicted in Figure 1.

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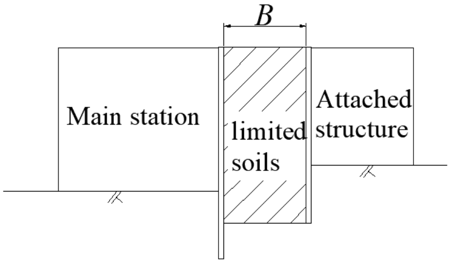


Fig. 1. limited soils diagram

For the calculation of earth pressure in confined spaces, there is currently no recognized method in the existing norms [1-2]. As a result, numerous scholars have conducted research on this topic. In terms of experiments, Frydman S, W.A. Take et al. [3-4] conducted centrifuge tests on earth pressure for limited soils with varying soil widths and discovered that the distribution of earth pressure for limited soils could be accurately described by the arch theory. Yang Minghui et al. [5] conducted a limited model test on earth pressure under different wall displacements. They discovered that the limited earth pressure was lower than the Coulomb's active earth pressure value. Additionally, they observed that the earth pressure initially increased and then decreased along the height of the wall under the translation mode. In terms of theoretical calculation, Ma Ping [6] derived a formula for calculating the active earth pressure of limited soils based on the limit equilibrium theory. This formula indicates that the shear failure angle of earth pressure for limited soils is not a constant value. Ying Hongwei et al. [7] used the horizontal layered thin layer element method to derive the theoretical formula for the distribution of active earth pressure and the position of the resultant force in limited soils. Wang Hongliang et al. [8] established a simplified equation for calculating the active earth pressure of limited soils by taking into account the interaction between the structure and limited soils. In terms of numerical simulation, Ying Hongwei et al. [7] used the finite element method to simulate the active earth pressure on the retaining wall of the adjacent basement. They found that a multi-channel slip surface would form in the limited soils. Xiao Xindi et al. [9] used discrete elements to study the development process of earth pressure for limited soils transitioning from a static state to an active state. The earth pressure for limited soils exhibits a nonlinear distribution and decreases gradually as the soil width decreases.

Based on the simplified calculation model of earth pressure in a finite space established by Ying Hongwei et al. [7], this paper deduces the calculation formula for the earth pressure on limited soils between the main station and the attached structure of the station. The formula takes into account the differences in overlying loads and bilateral contacts, and analyzes and studies the influential parameters.

2 Theoretical calculation derivation

Based on the research results presented above, this paper proposes a new model for calculating the earth pressure of limited soils, as illustrated in Figure 2. In this model, the sliding surface is assumed to be a plane. The interaction between the wall and soil is considered, and the limited soil is divided into two parts: a rectangular region and a triangular region (B is the width of the limited soil, H_1 represents the height of the limited soil acting on the connecting wall of the main structure, H_2 represents the height of the limited soil acting on the connecting wall of the auxiliary structure, and θ represents the inclination angle of the sliding surface). Wang Hongliang, Gao Yinli et al. [8, 10] found that it is reasonable to assume that the slip plane is a plane and the inclination of the slip plane is θ=45°+φ/2 after analyzing the overall force of the limited soils.

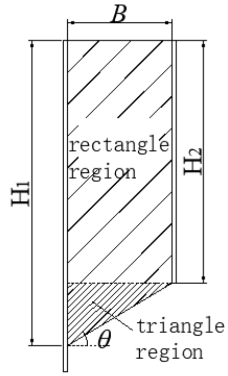


Fig. 2. limited soils calculation model

The soil is divided into horizontal layers, and the stress state is analyzed using the horizontal layered element method, as depicted in Figure 3. (τ' represents the shear force acting on the soil sliding surface, σ_m represents the normal force acting on the soil sliding surface)

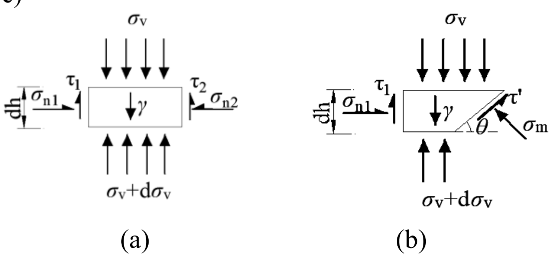


Fig. 3. limited soils horizontal thin layer stress state diagram

It can be obtained from the equilibrium condition of the vertical force in Figure 3(a):

$$B\sigma_v + \gamma B \mathrm{d}h = B\left(\sigma_v + \mathrm{d}\sigma_v\right) + \left(\tau_1 + \tau_2\right)\mathrm{d}h \tag{1}$$

Where: B represents the limited width of the soils; σ_v denotes the vertical stress; dh refers to the thickness of the horizontal stratified element. γ represents soil bulk density. τ_1 represents the shear force acting on the left side of the horizontal stratified element. τ_2 represents the shear force acting on the right side of the horizontal stratified element. σ_{n1} represents the normal force acting on the left side of the horizontally stratified element. σ_{n2} represents the normal force acting on the right side of the horizontally stratified element.

$$\tau_{1,2} = k_{1,2} \tan \delta_{1,2} \cdot \sigma_v = \beta_{1,2} \sigma_v \tag{2}$$

In the formula, k_1 and k_2 represent the pressure coefficients of the left and right sides, respectively. δ_1 and δ_2 denote the interface friction angles on the left and right sides, respectively. β_1 and β_2 are dimensionless coefficients.

Substitute equation (2) into equation (1) to simplify.

$$\sigma_v = p + \left(\frac{B\gamma}{\beta_1 + \beta_2} - p \right) \left[1 - e^{-\frac{(\beta_1+\beta_2)h}{B}} \right] \tag{3}$$

The lateral earth pressure acting on the main ground connecting wall is (0≤h≤H_2):

$$\sigma_{n1} = k_1 p + \left(\frac{k_1 \gamma B}{k_1 \tan \delta_1 + k_2 \tan \delta_2} - k_1 p \right) \left(1 - e^{-\frac{k_1 \tan\delta_1 + k_2 \tan\delta_2}{B} h} \right) \tag{4}$$

The lateral earth pressure acting on the ground connecting wall of the attached structure is (0≤h≤H_2):

$$\sigma_{n2} = k_2 p + \left(\frac{k_2 \gamma B}{k_1 \tan \delta_1 + k_2 \tan \delta_2} - k_2 p \right) \left(1 - e^{-\frac{k_1 \tan\delta_1 + k_2 \tan\delta_2}{B} h} \right) \tag{5}$$

Mohr's circle of stress at the interface is analyzed, as shown in Figure 4:

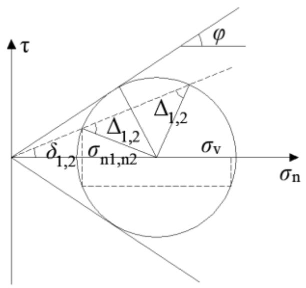


Fig. 4. Mohr's circle of stress in interfacial soil

From the geometric relationship in Figure 4:

$$\beta_{1,2} = \frac{\tau_{1,2}}{\sigma_v} = \frac{\sin\varphi \sin\left(\Delta_{1,2} - \delta_{1,2}\right)}{1 + \sin\varphi \cos\left(\Delta_{1,2} - \delta_{1,2}\right)} \tag{6}$$

$$k_{1,2}=\frac{\sigma_{\mathrm{n1,n2}}}{\sigma_{\mathrm{v}}}=\frac{1-\sin\varphi\cos\left(\Delta_{1,2}-\delta_{1,2}\right)}{1+\sin\varphi\cos\left(\Delta_{1,2}-\delta_{1,2}\right)} \tag{7}$$

Among them:

$$\sin\Delta_{1,2}=\frac{\sin\delta_{1,2}}{\sin\varphi} \tag{8}$$

From the equilibrium condition of horizontal force in Figure 3 (b), it can be obtained:

$$\sigma_{\mathrm{n1}}\mathrm{d}h+\tau'\cos\theta\frac{\mathrm{d}h}{\sin\theta}-\sigma_{m}\sin\theta\frac{\mathrm{d}h}{\sin\theta}=0 \tag{9}$$

Among them,

$$\tau'=\sigma_{\mathrm{m}}\tan\varphi \tag{10}$$

Substituting formula (10) into formula (9) simplifies to:

$$\sigma_{m}=\sigma_{\mathrm{n1}}\frac{\sin\theta\cos\varphi}{\sin\left(\theta-\varphi\right)} \tag{11}$$

From the equilibrium condition of vertical force in Figure 3 (b), it can be obtained:

$$\sigma_{\mathrm{v}}\left(\mathrm{H}_1-h\right)\cot\theta+\gamma\cdot\frac{1}{2}\left[\left(\mathrm{H}_1-h\right)\cot\theta+\left(\mathrm{H}_1-h-\mathrm{d}h\right)\cot\theta\right]\mathrm{d}h=\tau_1\mathrm{d}h+\sigma_{m}\cos\theta\frac{\mathrm{d}h}{\sin\theta}$$
$$+\tau'\sin\theta\frac{\mathrm{d}h}{\sin\theta}+\left(\sigma_{\mathrm{v}}+\mathrm{d}\sigma_{\mathrm{v}}\right)\left(\mathrm{H}_1-h-\mathrm{d}h\right)\cot\theta \tag{12}$$

By substituting formula (2), formula (7), formula (10) and formula (11) into formula (12), we can get:

$$\frac{\mathrm{d}\sigma_{\mathrm{v}}}{\mathrm{d}h}+\left\{k_1\left[\tan\delta_1+\cot\left(\theta-\varphi\right)\right]\tan\theta-1\right\}\frac{\sigma_{\mathrm{v}}}{\mathrm{H}_1-h}=\gamma \tag{13}$$

Make,

$$\mathrm{M}=k_1\left[\tan\delta_1+\cot\left(\theta-\varphi\right)\right]\tan\theta-1 \tag{14}$$

Then the formula (14) can be simplified to:

$$\sigma_{\mathrm{v}}=\mathrm{C}\left(\mathrm{H}_1-h\right)^{M}+\frac{\gamma}{\mathrm{M}-1}\left(\mathrm{H}_1-h\right) \tag{15}$$

Where C is a constant when the boundary condition h=H_2

$$Q_1=\sigma_{n1|h=H_2}=k_1p+\left(\frac{k_1\gamma B}{k_1\tan\delta_1+k_2\tan\delta_2}-k_1p\right)\left(1-e^{-\frac{k_1\tan\delta_1+k_2\tan\delta_2}{B}H_2}\right) \tag{16}$$

Substituting formula (16) into formula (15) yields:

$$\sigma_v=\left[Q_1-\frac{\gamma}{M-1}(H_1-h)\right]\left(\frac{H_1-h}{H_1-H_2}\right)^M+\frac{\gamma}{M-1}(H_1-h) \tag{17}$$

Therefore, the earth pressure of limited soils acting on the main ground wall is:

$$\sigma_{n1}=\begin{cases}k_1p+\left(\dfrac{k_1\gamma B}{k_1\tan\delta_1+k_2\tan\delta_2}-k_1p\right)\left(1-e^{-\frac{k_1\tan\delta_1+k_2\tan\delta_2}{B}h}\right) & (0\le h\le H_2)\\ k_1\left[Q_1-\dfrac{\gamma}{M-1}(H_1-H_2)\right]\left(\dfrac{H_1-h}{H_1-H_2}\right)^M+\dfrac{k_1\gamma}{M-1}(H_1-h) & (H_2<h\le H_1)\end{cases} \tag{18}$$

The earth pressure of limited soils acting on the ground connecting wall of the attached structure is:

$$\sigma_{n2}=k_2p+\left(\frac{k_2\gamma B}{k_1\tan\delta_1+k_2\tan\delta_2}-k_2p\right)\left(1-e^{-\frac{k_1\tan\delta_1+k_2\tan\delta_2}{B}h}\right) \quad (0\le h\le H_2) \tag{19}$$

Among them,

$$H_1=H_2+B\tan\theta \tag{20}$$

In equations (18) and (19), p, γ, B, δ_1, δ_2, φ, H_2 are the calculation parameters, while the remaining parameters can be derived from these values.

3 Analysis of influencing factors

3.1 Soil width

To analyze the influence of soil width on earth pressure of limited soils, the horizontal earth pressure is calculated under the following conditions: B=0.1H_2, 0.2H_2, 0.3H_2, 0.4H_2, and 0.5H_2. Other parameters are shown in Table 1. The calculation results are shown in Figure 5. As can be seen from Figure 5, with the increase in soil width, the earth pressure on both sides of the confined soil also increases. The left acting area of the limited soils increases with the increase in soil width. The earth pressure of the limited soils on the left reaches its maximum value at 20m, which is the boundary between the rectangular area and the triangular area. When the depth continues to increase, the earth pressure of limited soils on the left side decreases. The earth pressure of limited soils on the right side increases with increasing depth.

Table 1. Calculation parameters of earth pressure for limited soils

Overlying load P (kPa)	Soil bulk density γ (kN·m^{-3})	Left interface frictional Angle δ_1 (°)	Right interface frictional Angle δ_2 (°)	Soil internal frictional Angle φ (°)	The height of the attached structure is connected to the wall H_2 (m)
10	16	25	28	35	20

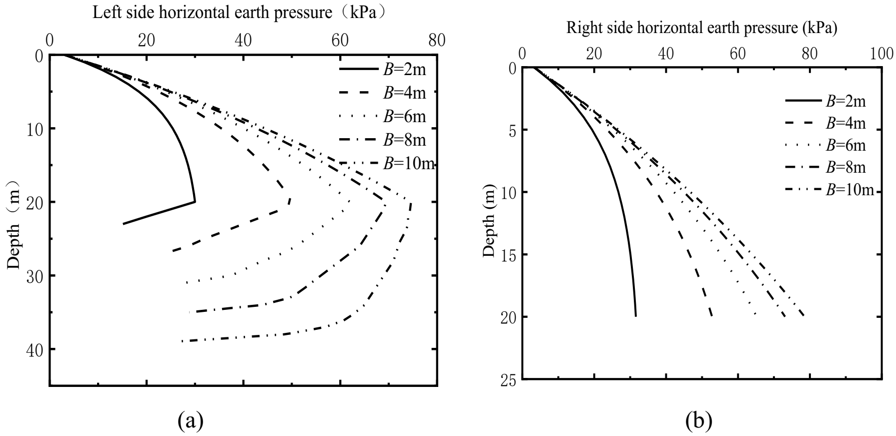
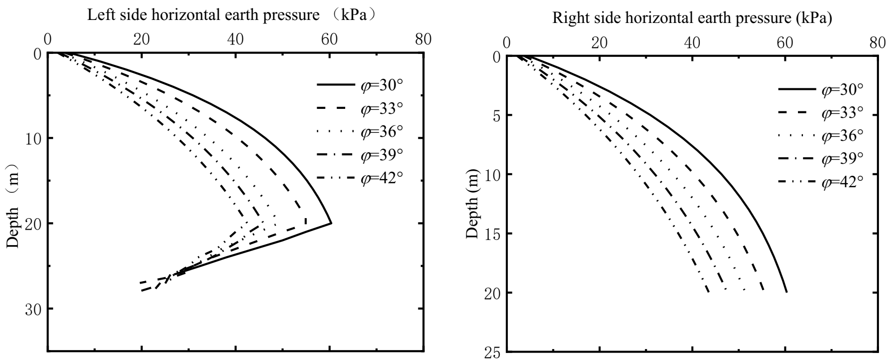


Fig. 5. Distribution of earth pressure on both sides of limited soils under varying soil widths

3.2 Soil internal frictional angle

In order to analyze the influence of the internal friction angle of the soil on the earth pressure of confined soils, the horizontal earth pressure was calculated under working conditions where the internal friction angle φ=30°, 33°, 36°, 39°, and 42°. The calculations were performed with a value of $B=0.2H_2=4$m, while keeping other parameters consistent with Table 1. The calculation results are shown in Figure 6. It can be seen from Figure 6 that the soil pressure on both sides of the confined soil decreases with an increase in the internal friction angle of the soil. The main reason for the analysis is that the internal frictional angle of the soil increases, resulting in the strengthening of the structure. This, in turn, leads to a decrease in the horizontal earth pressure exerted on the ground connection wall. When the internal friction angle is small, the earth pressure of limited soils changes significantly.



(a) (b)

Fig. 6. Distribution of earth pressure on both sides of confined soils under varying internal friction angles

3.3 Friction angle of the wall-soil interface

In order to analyze the influence of the frictional angle at the wall-soil interface on the earth pressure of confined soils, the horizontal earth pressure was calculated under the following conditions: B=0.1H_2=2m, δ_1=25°<δ_2=28°; B=0.2H_2=4m, δ_1=δ2=28°; B=0.3H_2=6m, δ_1=28°>δ_2=25°. Other parameters were consistent with Table 1. The calculation results are shown in Figure 7. As can be seen from Figure 7, when the interface frictional angles of the left and right sides of a confined soil are the same, the horizontal earth pressure on the left side in the rectangular region is equal to the horizontal earth pressure on the right side. If the interface friction angles on the left and right sides are different, the horizontal earth pressure on the side with the larger interface friction angle is larger.

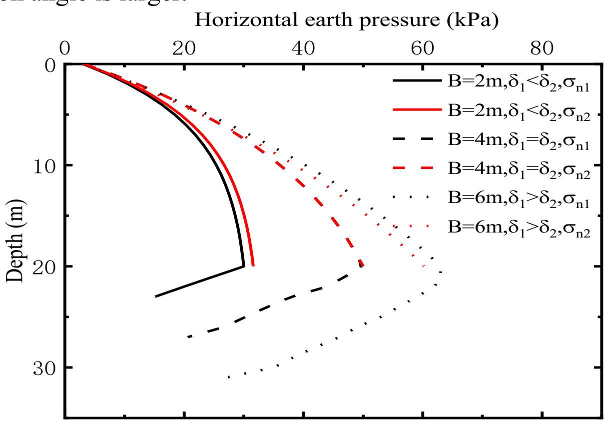


Fig. 7. Distribution of earth pressure on both sides of limited soils under different interfacial frictional angles

4 Conclusions

In this paper, the limited soil is divided into rectangular soil and triangular soil, and mechanical analysis is carried out. The influence of parameters on the earth pressure of limited soils is further considered, and an engineering example is calculated. The main conclusions are as follows:

(1) Taking into account the superimposed load and the varying roughness of the left and right sides of the confined soils, the theoretical calculation formula for the earth pressure of confined soils is derived using the horizontal stratification element method.

(2) The earth pressure of limited soils is distributed in an arched shape along the depth. When the depth is less than the height of the starting point of the slip surface, it increases with depth; when it is greater than the depth, it decreases with depth.

(3) The earth pressure of limited soils increases with the increase in soil width, the decrease in soil internal friction angle, and the increase in interface friction angle. The width of the soil has the most significant impact on the earth pressure of confined soils, followed by the internal friction angle of the soil and the friction angle at the interface.

The theoretical calculation method in this paper primarily focuses on the distribution of earth pressure of limited soils under conditions where there is no groundwater. In fact, groundwater is commonly present in construction projects and has a significant impact on the earth pressure of retaining walls. Therefore, future research should consider the influence of groundwater on the calculation of earth pressure of limited soils.

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