Simulation of Passive Earth Pressure against Retaining Wall Considering Wall Movement Mode

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Abstract. This paper investigated the effect of wall movements on passive pressure in sands by developing numerical simulation based on finite difference method for plane strain condition. A series of simulations was conducted under different wall movement modes (i.e. translation, rotation about a point below the wall, RB, and rotation about a point above the wall, RT). It is concluded that the distribution of passive earth pressure, magnitude and points of application are much affected by the wall movement modes. In addition, the effect of soil-wall friction angle on passive pressure is investigated. Simulation results indicate: the mode of wall movement has great influence on the passive earth pressure, and the heights of the application point in these three modes sort as: $RB > T > RT$.

Keywords: passive earth pressure; wall movement mode; numerical simulation.

1. Introduction

Earth pressure problem has always been one of the main topics in civil engineering, municipal engineering and water conservancy engineering. In practical engineering, because the calculation method of limit equilibrium theory, especially Coulomb theory, is simple and applicable, and can meets the requirements of engineering safety, it is still widely used in engineering. However, the classical Coulomb theory only assumes the limit equilibrium theoretical solution of the wall in the translation mode, and does not consider the earth pressure under other wall movement modes. Moreover, the linear distribution of the earth pressure obtained by the classical earth pressure theory is inconsistent with the actual situation. Tsagareli [1] and Fang et al. [2] show that the earth pressure behind the retaining wall is nonlinear distribution by a large number of test results.

In order to further study the earth pressure problem, many scholars have carried out theoretical research as well as numerical simulation. Some scholars (among others, Liu and Yu [3], Paik [4], Zhou et al. [5]) conducted theoretical research on earth pressure based on soil arching effect and limit equilibrium theory, and obtained the nonlinear distribution of earth pressure; Zeng and Zhou[6] studied the passive earth pressure of rigid retaining wall with different movement modes by PFC2D; Chen [7] simulated the earth pressure of retaining wall under different movement modes using finite
element method and discussed the influence of movement modes, soil-wall friction angle and other factors on the magnitude and distribution of earth pressure.

In this paper, the finite difference method is used to simulate the passive earth pressure, and the effect of different wall movement modes is considered, and the simulation results is compared with the results of coulomb theory. In addition, the influence of the soil-wall friction angle on the passive earth pressure is studied by simulating the variation of the magnitude and action position of the earth pressure on the wall under different soil-wall friction angles.

2. Numerical model and simulation scheme

2.1. Numerical model
The distribution of passive earth pressure and its height of application points behind the rigid retaining wall are simulated and analyzed. It is assumed that the retaining wall is upright, the surface of the soil layer is level and there is no load. We here consider the earth pressure as a plain strain problem and the numerical model is shown in Fig. 1.

Figure 1. The numerical model of retaining wall

2.2. Model parameters
The backfill behind the wall is 4.9m high and 16m long, with a grid number of 22×72, and the wall adopts beam elements. The bottom of the movable wall is 0.9m away from the bottom of the soil, as shown in Fig.1. A contact surface is set between the wall and the soil to simulate the wall-soil interaction. Table 1 shows the soil property parameters which is corresponding to the Ottawa sand investigated experimentally by Fang et al. [8].

| Bulk modulus $K$/MPa | Shear modulus $G$/MPa | Density $\rho$ kg/m$^3$ | Dilatancy angle $\phi$ |
|----------------------|-----------------------|--------------------------|------------------------|
| 60                   | 22.5                  | 2000                     | 1/3 $\phi$             |

Table 1. Backfill parameters

| $\phi$ | $\delta$ |
|--------|----------|
| 30$^\circ$ | $(1/3)\phi$ |
| 35$^\circ$ | $(2/3)\phi$ |

Table 2. Internal and soil-wall friction angles

In order to study the influence of the soil-wall friction angle on the earth pressure, three groups of different internal friction angles $\phi$ for different soil-wall friction angles are simulated, as shown in Table 2.

2.3. Calculation of passive earth pressure
For sands, the required wall displacement in T mode is more than 15%H, and in rotation mode is more than 10%H. (H is the height of wall.) In this simulation, thus, the wall displacement of T mode is 15%H, and the maximum wall displacement in rotation mode is 10%H.
In the process of simulation, the horizontal stress of the soil elements close to the wall is monitored. After the simulation is completed, the magnitude of the earth pressure acting on the wall can be calculated according to

\[ P_i = \sum \sigma_i h_i \]  
\[ P = P_x / \cos \delta \]  

where \( h_i \) is the grid height, \( P_x \) is the horizontal earth pressure of the grid, \( \delta \) is soil-wall friction angle, and \( P \) is the total passive earth pressure.

The passive earth pressure coefficient \( K_p \) can be calculated by

\[ K_p = \frac{1}{2} \gamma H^2 \]  

And the height of application point of earth pressure \( a \) may be estimated through the following expression based on moment balance:

\[ a = \sum \sigma_i h_i x_i / P \]  

where \( x_i \) is the height of the \( i \)-th grid from the bottom of the wall.

3. Numerical simulation analysis

3.1. T mode

Figure 2 shows the numerical model after simulation in translation mode. It can be seen that the grid near the wall has greater deformation, while the grid far away from the wall has less deformation, and the soil behind the wall slides upward along the wall.

![Figure 2. The numerical model after calculation](image_url)

Figure. 3 shows the horizontal stress of the backfill when the wall reaches passive state under the translation mode. It can be seen from figure 3 that the horizontal stress of the soil element near the wall is higher. In addition, the horizontal stress increases gradually with the increase of depth. The comparison of figure (a), (b) and (c) shows that with the increase of internal friction angle, the horizontal stress increases.
Figure 3. Horizontal stress in translation mode

Figure 4 describes the displacement of the soil behind the wall. It can be seen that the soil near the wall has a larger displacement than the soil far away from the wall. Besides, the displacement direction is upper right and a sliding surface emerges in the backfill. With the increase of distance from the wall, the displacement of the soil decreases, and the displacement of soil adjacent the right wall is almost zero. Furthermore, the magnitude and direction of the principal stress has been also analysed as shown in Fig.5. It can be seen from figure 5 that the soil element close to the wall has a high stress level while the stress is lower of the soil element far away from the wall. The direction of the major principal stress of the upper right part of the soil is roughly horizontal, and the lower left part of the soil near the wall is inclined, which is greatly influenced by soil arching effect.

Figure 4. Displacement vector in T mode

Figure 5. Vector of the Principal stress in T mode

Figure 6. Passive earth pressure distribution in translation mode (a) $\delta / \varphi = 1/3$; (b) $2/3$
As can be seen from Figure 6, when the soil-wall friction angle is small, the distribution of passive earth pressure is approximately linear. When the soil-wall friction angle becomes larger, the soil pressure above the wall is also approximately linearly distributed, but the stress has a big fluctuation at the bottom of the wall. The greater the internal friction angle is, the more obvious the fluctuation will be. According to the two figures Fig.6(a) and (b), it can be seen that the soil-wall friction angle has little influence on the earth pressure distribution, and only changes greatly at the bottom.

3.2. RB mode

It can be seen from Figure 7 that the sliding soil body, under RB mode, is relatively small and the slip surface is an approximate plane. Compared with the translation mode, the sliding displacement of the soil along the wall is large. In the other hand, as shown in figure 8, most of the major principal stress direction of soil is lower right, only the soil near the right boundary has horizontal major principal stress direction. Different from the translation mode, the principal stress of the soil on the right side does not decrease, and the principal stress of some soil even higher than that of the soil near the wall. The direction of the major principal stress in the sliding body is roughly arched, also indicating that there is soil arching effect in the soil body.

As shown in Fig.9, it is obvious that the earth pressure in RB mode is roughly parabolic, which first increases along the depth and then begins to decrease at a certain height above the bottom, and shows an obvious nonlinear distribution.

3.3. RT mode

Figure 10 depicts the displacement vector of the grid. In the RT mode, the size of the sliding soil is between the T and RB modes, and the soil displacement on the right side of the sliding surface is almost zero. The surface of the sliding body is hat-shaped, with low on both sides, high in the middle. As for the stress in the RT mode shown in Fig. 11, for the soil element close to the middle and upper part of the wall, the stress is very small, while the stress in the lower part suddenly increases. It can also be seen that there is an obvious soil arching effect in backfill.
Figure 10. Displacement vector in RT mode

Figure 11. Vector of the principal stress in RT mode

Figure 12. Passive earth pressure distribution in RT mode

Figure 12 shows the horizontal earth pressure distribution near the wall in RT mode. It can be seen that the earth pressure within 1.5m depth is very small, and it increases sharply below 1.5m. However, the earth pressure decreases close to zero at the bottom. The earth pressure reaches its maximum value near 3.5m depth. The earth pressure distribution is therefore also obviously nonlinear in RT mode.

4. Parameter analysis
In this section, the influence of soil-wall friction angle and wall movement mode on the passive earth pressure distribution, the height of application point and the magnitude of resultant force is analysed and compared with Coulomb earth pressure theory.

4.1. Effect of soil-wall friction angle on earth pressure
Figure 13 shows the variation of $K_p$ in terms of internal friction angle $\varphi$ under different soil-wall friction angles ($\delta / \varphi = 1/3$ or $2/3$). As shown in Figure 13, the influence of soil-wall friction angle on $K_p$ increases with the increase of the soil-wall angle. The value of $K_p$ increases with the increase of soil-wall friction angle with a difference of 30%-40%. For the lower soil-wall friction angle, the simulation results are close to the Coulomb theory which is generally smaller than the simulation results. For the higher soil-wall friction angle, the simulation results and Coulomb theory are coincident for lower internal friction angle, but are different with internal friction angle increases.
As shown in Figure 14, the height of the application point of passive earth pressure increases moderately with the increase of soil-wall friction angle. Compared with Coulomb theory, the height of the application point of passive earth pressure is higher, which illustrates that the distribution of passive earth pressure is not triangular.

4.2. Effect of movement mode on passive earth pressure

The distribution of earth pressure under different movement modes are shown in Figure 15, which illustrates that movement mode has a significant influence on earth pressure distribution. For T mode, the distribution of earth pressure is linear but it is approximately parabolic for RB mode; while for RT mode, the upper pressure is very small, and the lower pressure increases rapidly which is non-linear, which is similar to the experiment results of Fang et al. [8].

The movement mode of retaining wall is defined quantitatively:

\[
    n = \frac{S_{down} - S_{up}}{S_{max}}
\]

where \(S_{down}\) and \(S_{up}\) are the horizontal displacement of the bottom and top of the retaining wall respectively, and \(S_{max}\) is the maximum horizontal displacement of the retaining wall. Note that, the value of \(n\) is -1, 0, 1 for RB mode, T mode and RT mode respectively.

Figure 15. The effect of wall movement mode on earth pressure distribution
One can see from Figure 16 that the movement mode has a significant influence on the earth pressure. Under a certain internal friction angle, the value of $K_p$ for RB mode and RT mode is approximately equal but lower than that for T mode. The deviation between the value of $K_p$ for T mode and that for both RB mode and RT mode creases with the increase of the internal friction angle. Figure 17 shows the relation between the movement mode and the height of the application point $a$. One can see that the variation trend of $a$ is presented as: $RB > T > RT$. The values of $a$ for both RB mode and T mode deviate little and are larger than that for Coulomb theory. However, the value of $a$ for RT mode is lower than that for Coulomb theory, and the deviation with RB mode and T mode increases with internal friction angle increases.

5. Conclusion
1. The soil-wall friction angle has a significant effect on the earth pressure and little effect on the height of application point. As the soil-wall friction angle increases, the $K_p$ increases significantly. There is a soil arching effect in the sliding soil, and the direction of the major principal stress presents a concave arch for passive earth pressure.

2. The movement mode has a great influence on the passive earth pressure. In the T mode, the distribution is approximately linear, in the RB mode, the distribution is approximately parabolic, and in the RT mode, the upper pressure is very small, and the lower pressure increases rapidly. When the soil-wall friction angle is constant, the $K_p$ value in the T mode is greater than the $K_p$ value in the RB and RT modes, and the $K_p$ value in the RB and RT modes is approximately equal. As the soil-wall friction angle increases, the difference between the $K_p$ value in the T mode and the RB (or RT) mode becomes larger.

3. The height of application point shows a trend of $RB > T > RT$. The difference of application point for RB and T modes is very small, and both are greater than the height of the application point calculated by Coulomb theory; The height of the application point under RT mode is smaller than that calculated by Coulomb theory.

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