Study on non-limit active earth pressure of finite soil under T mode

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Abstract. Under the T (translation) mode, the active earth pressure of the limit soil is closely related to the displacement of the retaining wall and the width of the backfill of the wall. Based on the plane sliding assumption, fully considering the influence of the width of the backfill wall and the displacement of the wall on the internal and external friction angles, a balance equation is established, and the different backfill widths of the wall under any translational displacement are derived Formula of active earth pressure. The analysis shows that the fracture angle of the soil decreases with the increase of the soil width, decreases with the increase of the displacement or decreases first and then increases; the size of the active earth pressure of the limited soil decreases with the increase of the displacement; its soil pressure distribution intersects with the Coulomb earth pressure distribution depends on the width-to-height ratio of the fill. The intersection point gradually transitions from the bottom of the wall to the top of the wall as the ratio of displacement to the limit displacement increases, only when the width-to-height ratio is not less than 0.5 and the displacement reaches the limit. The solution in this paper is approximately equal to the Coulomb solution.

1. Introduction
With the continuous expansion of construction and repair in China, and the limited land resources, more and more retaining walls are built very close to the rock mass or existing buildings (Fig. 1). This makes it extremely unreasonable to use the traditional Rankine theory or Coulomb theory to calculate the active earth pressure on the retaining wall.

Based on the calculation of active earth pressure with only limited soil behind the wall, many scholars at home and abroad have done a lot of research for this purpose. HANDY R L (2008) obtained the calculation formula of the earth pressure behind the wall by conducting the stress analysis of the thin layer element on the limited soil. GAO Yin-li et al. (2000) deduced the calculation formula of the active and passive earth pressure through the energy balance analysis of the limited cohesive soil behind the wall through the plastic upper limit theory, and the results are quite different from the values obtained by the Rankine earth pressure theory. YING Hong-wei et al. (2011) obtained the analytical formulas of the fracture angle and the earth pressure coefficient of the limited soil body under the active limit state by considering the assumption that the soil body is overloaded, based on the assumption of the Coulomb plane. WANG Hong-liang et al. (2014) also analyzed the stress on both sides of the limited soil body, and obtained a simplified formula for the calculation of earth pressure, which was in good agreement with the simulation value of plaxis software. YUE Shu-qiao (2016) analyzed the finite soil mass between two foundation pits through the principle of silo stress, and simplified it appropriately, and obtained the calculation formula of its active earth pressure force.
The theoretical value is basically consistent with the simulated value. YANG Ming-hui et al. (2017) obtained through experiments that the failure surface of the limited soil body was a curved surface, and based on the variational principle, it was obtained that the curved surface substantially satisfied the logarithmic spiral equation. WANG Yan-chao et al. (2016) established a calculation model for the inclined back of the wall and uniformly overloaded the limited fill surface, deduced the calculation formula for the active earth pressure of the retaining wall under more complicated conditions, and compared it with the numerical solution. XU Ri-qing et al. (2013, 2020) took cohesive soil as the research object, and considered the effect of displacement of the wall through the thin layer element method, and obtained the theoretical calculation formulas of the distribution, resultant force, and position of the non-limit active earth pressure. And this method is applied to the solution of finite active earth pressure. LIU Zhong-yu et al. (2016, 2018) took non-cohesive soil as the research object, deduced the formula solution of the active earth pressure of the rigid retaining wall through the horizontal layer strip method, and considered the shear action between the soil layers. The experimental and predecessor theoretical solutions were compared and analyzed. On this basis, this method was extended to the solution of the finite earth pressure of cohesionless soil. HU Wei-dong et al. (2019) conducted a passive earth pressure test study on a flexible retaining wall with limited width non-cohesive sand cantilever row piles, and found that with the wall displacement and soil width increasing, the passive earth pressure on the wall is significantly greater than that of the lower part, and the lower earth pressure value tends to be more stable.

Existing literature is basically about the earth pressure of the limited soil body when it reaches the limit displacement, and the retaining wall often cannot reach the limit displacement during actual use. Based on this, in this paper, through the assumption of plane sliding, the effects of displacement and the width-to-height ratio of the fill on the earth pressure of the retaining wall are fully taken into consideration. On the basis of this method, the effects of fill width and wall displacement on the fracture angle of the soil and the size of active earth pressure are discussed, and they are compared with the classic Coulomb earth pressure theory.

Fig.1  Schematic diagram of the limited fill model

2. Derivation of active earth pressure theory for limit fill
When the back of the wall is subjected to the earth pressure of the limited fill, the wall will be displaced correspondingly due to external forces. When the displacement is greater than the limit displacement of the fill, the soil will be destroyed, which will cause the wall to overturn or slip. Stable; when the displacement is less than the limit displacement of the fill, the soil will not be destroyed and the wall will work normally, but how to solve the active earth pressure acting on the wall at this time will be the focus of this study.

As we all know, the internal friction angle of the soil is measured by causing it to produce a fracture surface, that is, a certain shear displacement occurs. Assuming the internal friction angle $\phi_m$ of the fill, the wall-soil friction angle $\delta_m$ and the wall displacement $S$ respectively have the following linear relationship:
\[ \varphi_m = \beta \varphi, \delta_m = \beta \delta \]  

In the formula, \( \beta = \frac{S}{S_a} \), where \( S_a \) represents the limit displacement value of the soil.

After establishing the relationship between \( \varphi_m, \delta_m \), and \( S \), the calculation model is shown in Fig. 2. The back of the wall is vertical, the fill surface is horizontal, its width is \( B \), and its height is \( H \), so that the aspect ratio is \( B/H = n \), the inclination angle of the sliding surface is \( \theta \), the force of the sliding bed on the sliding body is \( R \). The normal angle of the crack surface is \( \varphi_m \), the weight of the sliding crack is \( G \), the bulk density of the fill is \( \gamma \), and the active earth pressure on the back of the wall is \( E_a \).

It can be obtained by balancing the horizontal force

\[ \sum X = 0: \quad E \cos \delta_m - R \sin (\theta - \varphi_m) = 0 \tag{2} \]

It can be obtained by balancing the vertical force

\[ \sum Z = 0: \quad E \sin \delta_m + R \cos (\theta - \varphi_m) = G \tag{3} \]

Among them

\[ G = 0.5 \gamma H^2 n (2 - n \tan \theta) \tag{4} \]

The solution is

\[ E_a = \frac{\gamma H^2 n (2 - n \tan \theta) \sin (\theta - \varphi_m)}{2 \cos (\theta - \varphi_m - \delta_m)} \tag{5} \]

The active earth pressure \( E_a \) on the back of the wall is a function of the inclination angle \( \theta \) of the slip surface, then the most dangerous inclination angle \( \theta_c \) of the slip surface can be obtained by derivation

\[ \frac{dE_a}{d\theta} = 0 \tag{6} \]

The solution is

\[ \theta_c = \arctan \left[ -\cot (\varphi_m + \delta_m) + \sqrt{\cot^2 (\varphi_m + \delta_m) + \frac{n \sin \varphi_m \cos (\varphi_m + \delta_m) + 2 \cos \delta_m}{n \cos \varphi_m \sin (\varphi_m + \delta_m)}} \right] \tag{7} \]

Since it is difficult to obtain the distribution solution of the active earth pressure according to equation (5), it can be obtained by the following difference form:

\[ \left. \frac{dE_a}{dH} \right|_{H=\frac{H_2+H_1}{2}} = \frac{E_a|_{H=H_2} - E_a|_{H=H_1}}{H_2 - H_1} \tag{8} \]

The Coulomb rupture angle can be obtained by the following formula

\[ \theta_{cr} = \arctan \left( \frac{\tan \varphi}{\tan (\varphi + \delta) + \tan^2 \varphi + \tan \varphi} \right) \tag{9} \]
The formula for calculating Coulomb’s active earth pressure is

\[ E_c = \frac{\cos^2(\phi - \epsilon) \left[ 1 + \sqrt{\frac{\sin(\phi + \delta)\sin(\phi - \alpha)}{\cos(\epsilon + \delta)\cos(\epsilon - \alpha)}} \right]}{\cos \epsilon \cos(\epsilon + \delta)} \gamma h \]  

(10)

\( h \) is the filling depth of the calculation point.

From (7) (9) and (8) (10), it is found that the angle between the fracture surface and the Coulomb angle obtained in this paper is obviously different, mainly because the theoretical formula in this paper considers the limited soil behind the wall happening.

3. Parameter analysis

Fig.3 shows the relationship curve between \( \theta_c \) and \( \beta \) and \( n \). It can be found that the Coulomb rupture angle \( \theta_{cr} \) is always constant at 57°, and does not change with the wall displacement and soil width. However, the rupture angle obtained in this paper varies with the wall displacement. The increase decreases first, then increases slightly, and the smaller the soil width, the more the value exceeds the Coulomb solution. Only when the wall width is larger, it may occur less than the Coulomb solution, which is mainly due to the soil. The narrower, the weaker its ability to withstand the gravity of the soil, the easier it is to slide.

Fig.4, Fig.5, and Fig.6 respectively show active earth pressure distribution curves under different displacements when \( n = 0.1 \), \( n = 0.3 \), and \( n = 0.5 \). It can be found that the earth pressure on the back of the wall is distributed in a convex curve with a small upper and lower, and as the translational displacement of the wall increases, the earth pressure will decrease. This is mainly due to the increase in displacement, which will cause the filling. The internal friction angle of the soil is fully exerted, so that the energy dissipation inside the soil body increases, so the earth pressure acting on the back of the wall will be reduced. In the case of the same displacement of the wall, as the width of the backfill of the wall increases, the active earth pressure also increases, mainly due to the increase in the weight of the sliding crack due to the increase in soil width. Through the example in this paper, only when the width of the soil behind the wall is about half of the wall height, the solution in this paper basically converges to the Coulomb solution, which also fully shows that the Coulomb solution is a special solution of the solution in this paper. At infinity, the solution in this paper can be reduced to the Coulomb solution.

No matter how the displacement of the wall changes, whether the width of the fill increases, the Coulomb’s earth pressure remains constant and has a linear distribution, mainly because the Coulomb theory does not consider the effects of displacement and wall width during the derivation process, which also shows Coulomb theory has certain limitations in actual design. Under the same working conditions, whether the intersection between the solution and the Coulomb solution will mainly depend on the displacement and soil width. The larger the width and the larger the displacement, the less likely it is to intersect.
4. Conclusion

(1) Based on the plane sliding assumption, fully considering the influence of the width of the backfill wall and the displacement of the wall on the degree of internal and external friction angles, a balance equation is established, and the different fill widths behind the wall are arbitrarily translated Active earth pressure formula with displacement.

(2) The finite active earth pressures are distributed in a convex curve with a small top and a large bottom, and with the increase of the translational displacement of the wall, the earth pressure will decrease, and the width of the backfill of the wall will increase, so will the active earth pressure.

(3) Only when the width of the soil behind the wall is about half of the wall height, the solution in this paper basically converges to the Coulomb solution, which also fully shows that the Coulomb solution is a special solution of the solution in this paper.

References

[1] HANDY R L. The arch in soil arching[J]. Journal of Geotechnical Engineering, 2008,
[2] GAO Yin-li, The calculation of finite earth pressure[J]. Building Science, 2000, (05): 53-56.
[3] YING Hong-wei, HUANG Dong, Study on active earth pressures on translation retaining walls adjacent to existing basements[J]. Chinese Journal of Solid Mechanics, 2011, 32(S1): 356-360.
[4] WANG Hong-liang, SONG Er-xiang, SONG Fu-yuan. Calculation of active earth pressure for limited soil between existing building and excavation[J]. Engineering Mechanics, 2014, 31(04): 76-81.
[5] YUE Shu-qiao1, ZUO Ren-yu, LU Zhao. A method for calculating active earth pressure of soil piece with a finite width between adjacent foundation pits[J]. Rock and Soil Mechanics, 2016, 37(07): 2063-2069.
[6] YANG Ming-hui, DAI Xia-bin, ZHAO Ming-hua, et al. Calculation of active earth pressure for limited soils with curved sliding surface[J]. Rock and Soil Mechanics, 2017, 38(07): 2029-2035.
[7] WANG Yan-chao, YAN E-chuan, LU Wen-bo, et al. Analytical solution of active earth pressure for limited cohesionless soils[J]. Rock and Soil Mechanics, 2016, 37(09): 2513-2520.
[8] XU Ri-qing, LIAO Bin, WU Jian et al. Computational method for active earth pressure of cohesive soil under nonlimit state[J]. Rock and Soil Mechanics, 2013, 34(01): 148-154.
[9] XU Ri-qing, XU Ye-bin, CHENG Kang et al. A method to calculate the active earth pressure with considering soil arching effect under the nonlimit state of clay[J]. Chinese Journal of Geotechnical Engineering, 2020, 42(02): 362-371.
[10] LIU Zhong-yu, CHEN Jie, LI Dong-yang. Calculation of active earth pressure against rigid retaining wall considering shear stress[J]. Rock and Soil Mechanics, 2016, 37(09): 2443-2450.
[11] LIU Zhong-yu. Active earth pressure calculation of rigid retaining walls with limited granular backfill space. China J. Highw. Transp, 2018, 31(02): 154-164.
[12] HU Wei-dong, ZHU Xin-nian, ZHOU Xi-yu. Experimental study on passive earth pressures of cohesionless soils with limited width against cantilever piles flexible retaining walls[J]. Chinese Journal of Rock Mechanics and Engineering, 2019, 38(S2): 3748-3757.