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Characteristics of cantilever retaining wall of the ancient capital city in Fengyang

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Abstract: *In Zhongdu ancient city of Fengyang, based on the finite element method, the earth pressure and deformation of the cantilever retaining wall composed of upper wall and lower wall are compared and analyzed. The results show that the maximum lateral displacement of the fill occurs near the top of the upper wall, the lower wall has the tendency of overturning to the free surface, while the upper wall has a certain deviation from the free surface. The vertical earth pressure acting on the heel plate of the upper wall and the lower wall presents non-linear characteristics. When the cantilever retaining wall composed of upper wall and lower wall is unstable, there are two slip surfaces in the filling. The first slip surface runs through the filling based on the heel plate root of the lower wall, and the second slip surface runs through the upper filling based on the heel plate root of the upper wall.*

Key words: *cantilever retaining wall; the upper wall; the lower wall; lateral displacement; failure surface*

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The cantilever retaining wall is usually composed of three parts: the vertical arm panel, the toe plate and the heel plate, which are all made by reinforced concrete. The cantilever retaining wall mainly depends on the weight of filling on the floor plate to maintain its stability, which is priority adopted in areas where stone is scarce and the bearing capacity of foundation is low. According to China's technical specifications, the height of cantilever retaining wall should not be greater than 6m [1].

The existing literature mainly focuses on the one-level cantilever retaining wall, but in fact, the two-level or multi-level stacked cantilever retaining wall can also be used in exceptional circumstances[2-6]. The two-level or multi-level stacked cantilever retaining wall has gradually attracted the attention of engineering and academia. The deformations of retaining back and stresses of backfill have been analyzed by elastoplastic numerical calculation model to simulate construction conditions with two-level cantilever retaining wall by Liang Bo[7], which showed that the two- level cantilever retaining wall is feasible in force, and its application can be extended to the protection needs of higher slopes. Based on soil plasticity and limit analysis theory, the consideration of the cohesion force on the sliding plane, the adhesive force on the interface of between soil and two level structure of cantilever retaining wall has been studied by WANG Jing-huan et al[8], which results show that the stress distribution of upper and lower part of two level new structure of cantilever retaining wall are observed to present a parabola style and trapezium distribution separately, and the maximum and minimum respectively occurred in the bottom and middle of retaining wall. The case study of instability failure of multi-level cantilever retaining wall used in filling soil area was carried out by Zhang Yong et al[9], which shows that when the compactness of soil is poor and the internal friction angle is smaller than 20°, the soil slope is easy to form a whole slip rupture surface to cause instability of cantilever retaining wall, and emphasizes the importance of the quality of the fill soil construction and the drainage measures to the multi-level retaining structure in the filling soil area. Based on the limit equilibrium theory and considering the effect of the second failure surface, the various sliding surfaces of conterfort retaining wall is reasonable selected by Liang Qiao et al, which showed that the earth pressure and the stability of the counterfort retaining wall are more reasonable than the common retaining wall.

However, the design and calculation methods of the two-level cantilever retaining wall are not mature, and its mechanical and deformation properties need to be further explored. Therefore, based on the finite element method, this paper makes a comparative analysis of earth pressure and filling deformation of the two-level stacked cantilever retaining wall composed of upper wall and lower wall. By changing geometric parameters, the influencing factors of the stability of the retaining wall are discussed, which can provide some reference for accurately grasping the load characteristics of the two-level stacked cantilever retaining wall.

1 Finite element calculation model

In this paper, a typical two-level stacked cantilever retaining wall is analyzed. The sizes of the upper and lower retaining walls are the same. The height of the upper and lower retaining wall is H=5.5m, and the length of the heel plate is L=3.2m, the thickness of the reinforced concrete plate is 50 cm. The calculation model of the retaining wall is shown in Figure 1.

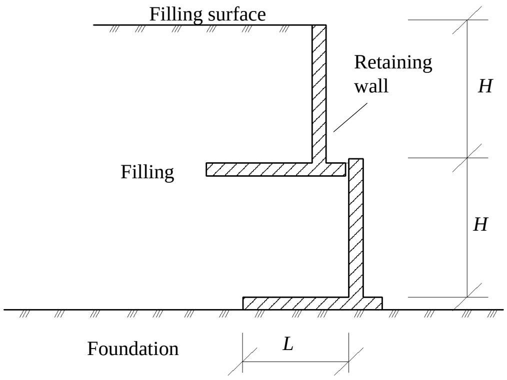


Fig. 1 Calculation model of cantilever retaining wall

In view of the large longitudinal length of the retaining wall and the unchanged size and shape of the cross section along the axis length, the plane strain finite element method (FEM) is used to analyze the retaining wall. Mohr-Coulomb ideal elastic-plastic model is adopted for the foundation and filling materials, and the retaining wall is reinforced concrete structure with high strength, which can be considered as linear elastic material. The calculation parameters of each soil layer and retaining wall are shown in Table 1.

Table 1 Physical and Mechanical Parameters of Soil Layers

Soil later	Weight /kN.m^{-3}	Cohesion c/kPa	Internal friction angleφ/(^{0})	Deformation modulus E_0/MPa	Poisson ratio
Foundation	19.4	48.5	36.7	137	0.28
Filling	17.1	11.3	28.6	7.6	0.34
Retaining wall	24.1			30000	0.21

In order to simulate the interface characteristics between retaining wall and soil, a thickness-free interface element can be set between them. The friction coefficient R is used to reflect the degree of interaction between retaining wall and soil. According to the experimental data in relevant literature[3], and combined with the physical and mechanical parameters of soil behind the wall, R=0.75 is selected in this calculation.

In the numerical calculation, the bottom side is fixed with no horizontal and vertical displacements, and horizontal displacement constraints at both sides. 15-nodes triangular element is used to mesh the calculation model. The mesh is refined at the contact point between the retaining wall and the filling soil and the interface between the soil layer, Fig. 2 shows the mesh partition of the finite element method.

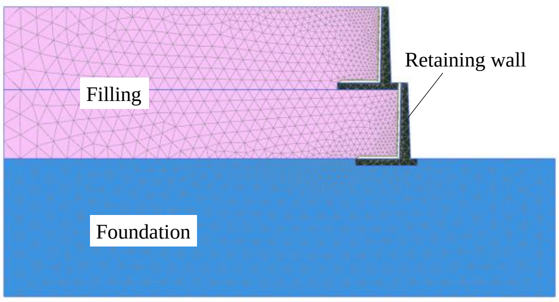


Fig. 2 Mesh of FEM (elements:2755)

The settlement of original foundation soil is completed before the construction of retaining wall. The construction process can be simulated by gradually activating the retaining wall and filling element. The location and safety factor of sliding surface of retaining wall can be investigated by strength reduction finite element method[11-14].

2 Results of calculation

Based on the finite element method, the earth pressure and filling deformation of retaining wall under different parameters are investigated, and the basic characteristics of two-level stacked cantilever retaining wall are obtained.

2.1 Deformation of filling

After construction, the isoline distribution of lateral displacement in the backfill is shown in Fig. 3, the lateral displacement of the vertical section at the back of the wall is shown in Fig. 4, and the vertical settlement in the backfill is shown in Fig. 5. The negative values in Fig. 3 and Fig. 4 indicate that the lateral displacement is opposite to the x-axis direction.

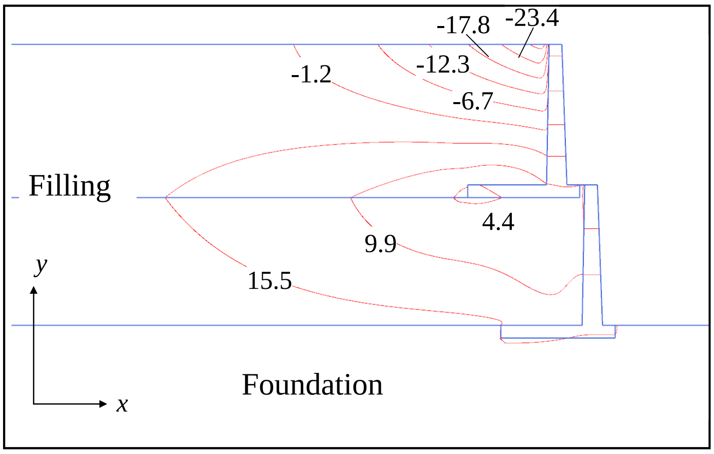


Fig. 3 Contours of lateral displacement in filling (unit: mm)

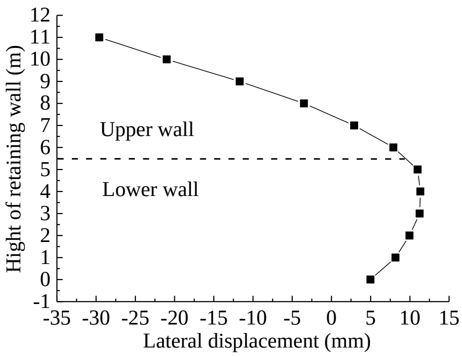


Fig. 4 Lateral Displacement on the Back of Retaining Wall

From Fig. 3 and Fig. 4, it can be seen that the maximum lateral displacement of the fill occurs near the top plate of the upper wall, and its value is -23.4mm, which direction deviation from the free surface. The farther the distance to the root of the heel plate of the upper wall is, the bigger the lateral displacement of the fill is. The lateral displacement of the fill near to the bottom of the upper wall is 4.4mm, which direction points to the free surface. It can be seen that the lateral displacement direction of the top and bottom of the upper wall is opposite, which shows that the upper wall has been deflected obviously.

It can be found that the direction of lateral displacement of the fill in the lower wall area develops towards the free surface, while the direction of lateral displacement of the fill at the lower part of the upper wall develops towards the free surface, and the direction of lateral displacement of the fill near the top of the upper wall develops in the opposite direction. The lateral displacement of the two-level stacked cantilever retaining wall is obviously different from that of the traditional single cantilever retaining wall. Usually, the direction of lateral displacement of a single cantilever retaining wall is directed to the free surface.

The variation of lateral displacement of two-level stacked cantilever retaining wall is related to its characteristics of retaining wall structure. The upper wall and the lower wall of the two- level stacked cantilever retaining wall are essentially separate and unrelated. The characteristics of the lower wall are similar to those of the traditional single cantilever retaining wall, and the lower wall tends to overturn to the empty surface.

But for the upper wall, on the one hand, the heel plate of the upper wall is pressed on the top of the lower wall filling surface, and the displacement of the filling within the lower wall makes the heel plate difficult to maintain the horizontal state, the displacement of the upper wall occurs with the displacement of the fill; On the other hand, the filling within the upper wall part is pressed on the heel plate of the upper wall, which further aggravates the displacement of the upper wall. According to the features of filling settlement, the upper wall will rotate away from the free surface, and eventually the lateral displacement of the filling will develop in the opposite direction to the free surface within a certain range of the top of the upper wall.

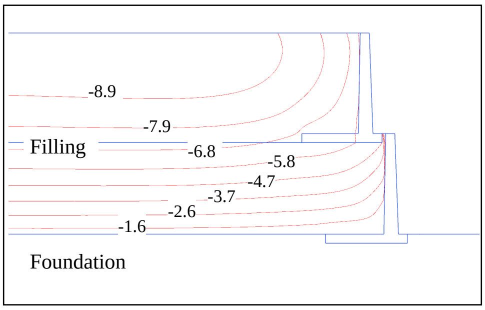
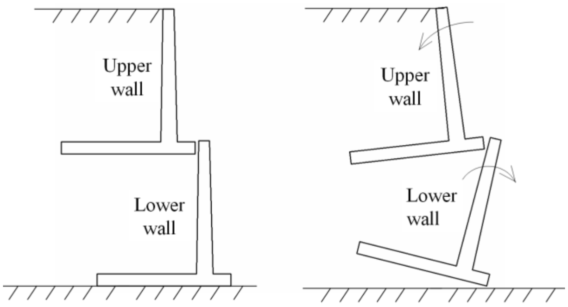


Fig. 5 Contours of vertical displacement in filling (unit: cm)

Fig. 6 further illustrates the movement trend of the upper wall and the lower wall. It can be seen that because there is no strong connection between the upper wall and the lower wall, the upper wall and the lower wall show different movement trends, which are determined by the deformation of the soil and the force of the retaining wall.



(a) Original state (b) Deformation trend

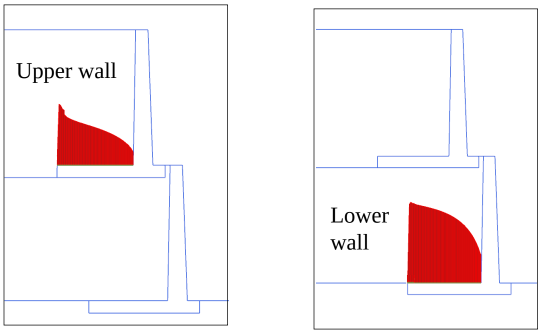
Fig. 6 Deformation trend of two-level cantilever retaining wall

The heel plate of the lower wall is pressed on the original foundation soil layer whose settlement has been completed, so its stability is relatively high. For the upper wall, the heel plate of the wall is pressed on the newly filled soil. If the compaction degree of the fill is not enough, the upper wall and the fill will move greatly together. It can be seen that the movement of the upper wall is not only related to the load it is subjected to, but also to the compactness of the fill under it. In order to improve the overall stability of the two-stage stacked cantilever retaining wall, the compactness of the fill (especially the fill at the bottom of the upper wall) should meet the requirements, and the sand and gravel with low compressibility and high strength should be preferentially used to fill the bottom of the heel plate of the upper wall.

2.2 Characteristics of Earth Pressure on Retaining Wall

Vertical earth pressure characteristics of heel plate of two-stage stacked cantilever retaining wall are shown in Fig. 7, and values of earth pressure are shown in Fig. 8. It can be seen that the vertical earth pressure on the upper wall and the heel plate of the lower wall presents non-linear characteristics. The closer the vertical earth pressure is to the wall root, the smaller the vertical earth pressure is. The farther away from the wall roots, the greater the vertical earth pressure.

For the upper wall, the minimum vertical earth pressure at the base of the wall is 27.0 kPa, and the maximum vertical earth pressure at the end of the wall heel is 115.1 kPa. The self-weight stress of the fill at the heel plate position of the wall is (5.5)*17.1= 94.05kPa. It can be seen that the vertical earth pressure of the wall heel plate at some locations is much less than the overlying soil weight, while the vertical earth pressure of the wall heel plate at other locations is greater than the overlying soil weight, and the maximum earth pressure coefficient is 1.223.



(a) Upper wall (b)Lower wall

Fig. 7 Shape of vertical earth pressure on heel plate of two-level stacked cantilever retaining wall

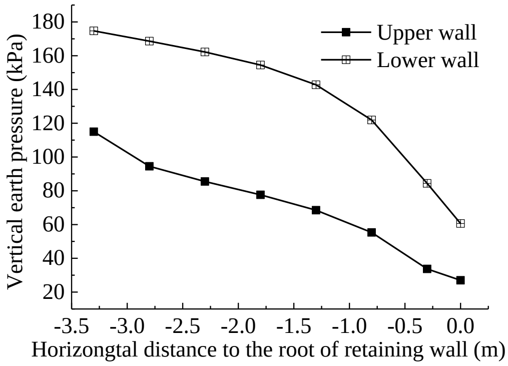
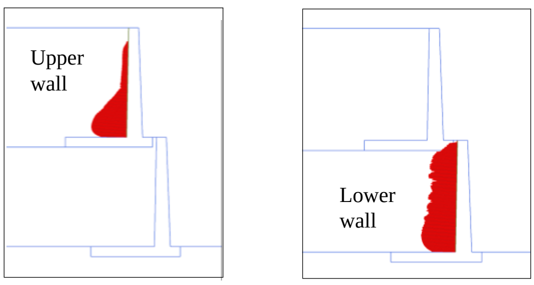


Fig. 8 Value of vertical earth pressure on heel plate of two-level stacked cantilever retaining wall

For the lower wall, the minimum vertical earth pressure at the base of the wall is 60.6 kPa, and the maximum vertical earth pressure at the end of the heel wall is 174.7 kPa. If the inclined fill with 1.0m thickness at the top of the fill is simply equivalent to the horizontal fill with 0.5m thickness, and the influence of the self-weight of the upper wall is neglected, the self-weight stress of the fill at the heel plate position of the lower wall is (5.5+5.0)*17.1= 179.5kPa. It can be seen that the maximum vertical earth pressure of the heel plate of the lower wall is basically the same as the overlying soil weight at that location, but the vertical earth pressure of the heel plate of the lower wall is much less than the overlying soil weight at some locations. Because of the deformation of the fill and the displacement of the retaining wall, the stress arch is generated in the filling, which makes the vertical earth pressure on the heel plate of the upper wall and the lower wall different from the overlying soil weight.

The characteristics of lateral earth pressure on the back of two-level stacked cantilever retaining wall are shown in Fig. 9, and the specific values of lateral earth pressure are shown in Fig. 10. It can be seen that the lateral earth pressure on the back of the upper wall and the lower wall presents non-linear characteristics. The distribution of lateral earth pressure on the back of the upper wall is similar to that of the traditional single cantilever retaining wall. The non-linear characteristics of lateral earth pressure have been confirmed by experimental data[15].



(a) Upper wall (b)Lower wall

Fig. 9 Shape of lateral earth pressure on back of two-level stacked cantilever retaining wall

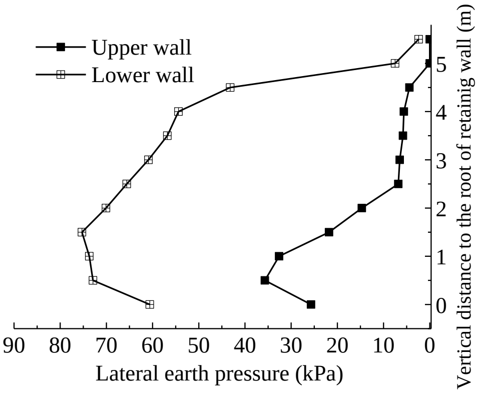


Fig. 10 Value of lateral earth pressure on heel plate of two-level stacked cantilever retaining wall

For the lower wall, the rigid heel plate of the upper wall is pressed on the top of the lower wall filling, which results in a large lateral earth pressure on the top of the lower wall, which is the embodiment of stress concentration. The maximum lateral earth pressure of the lower wall is 75.3kPa, which is located at the bottom of the heel plate of the upper wall. Under the joint influence of the heel plate pressure of the upper wall, the uneven settlement of the filling soil and the displacement of the lower wall itself, the lateral earth pressure on the back of the lower wall presents non-linearity. It is difficult to get the back lateral earth pressure of the lower wall of the two-level stacked cantilever retaining wall by the existing calculation theory. At present, there are few studies on lateral earth pressure of the lower wall in the existing literature, which need to be further explored through the test.

2.3 Stability of retaining wall

Based on the strength reduction finite element method, the position of slip surface of two-level stacked cantilever retaining wall is calculated, as shown in Fig. 11. It can be seen that there are two slip surfaces in the filling. The first slip surface runs through the filling based on the heel plate root of the lower wall, and the second one runs through the upper filling based on the heel plate root of the upper wall.

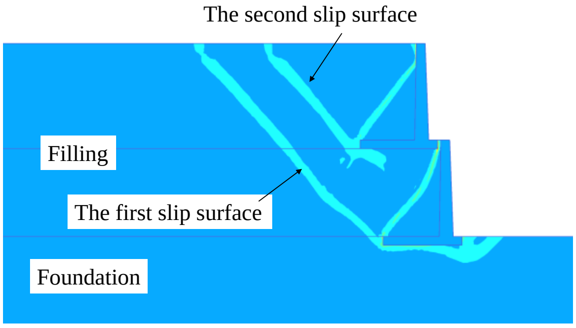


Fig.11 Location of slip surface of two-level stacked cantilever retaining wall

In engineering, the retaining wall with the second slip surface is defined as a flat wall[3,16]. However, the traditional flat wall usually refers to two potential slip surfaces in the backfill behind the same retaining wall. In fact, the retaining wall in this paper is two independent cantilever retaining walls. The two slip surfaces correspond to the upper and lower retaining walls respectively. Therefore, the two slip surfaces in this paper are different from those in the traditional flat wall.

When the displacement movement of the upper wall and the lower wall is finished, the bottom of the upper wall and the top of the lower wall overlap in the horizontal direction and do not break away, the upper wall can not escape the constraint of the lower wall and slide to the free surface. At this time, the overall slip surface is often controlled by the first slip surface of the lower wall. However, when the lower wall cannot restrain the movement of the upper wall, the slip surface of the fill may be the first slip surface in the lower part, or the second slip surface in the upper part. In special cases, two slip surfaces may occur simultaneously. Therefore, in order to maintain the overall stability of two-level stacked cantilever retaining wall, the vertical overlap height between the bottom of the upper wall and the top of the lower wall should not be too small.

The displacement increment distribution of the retaining wall on the verge of instability is shown in Fig. 12. It can be seen that a large displacement occurs in the fill above the position of the first slip surface, and the increment of displacement at the junction of the bottom of the upper wall and the top of the lower wall is larger,

which is consistent with the maximum lateral displacement at the location mentioned above.
For the two- level stacked cantilever retaining wall, besides the large stress at the bottom of the lower wall, the junction between the bottom of the upper wall and the top of the lower wall is also a weak link. It is helpful to grasp the basic characteristics of the stacked retaining wall accurately.

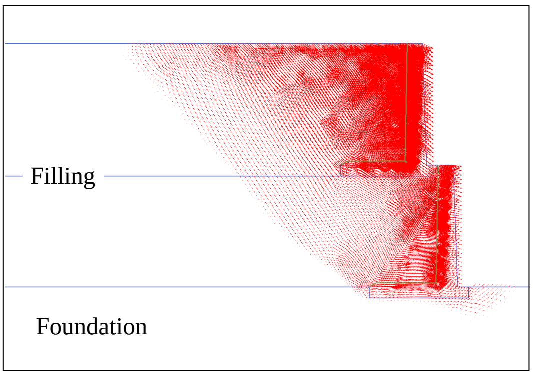


Fig. 12 Distribution of displacement increment of filling at failure state of retaining wall

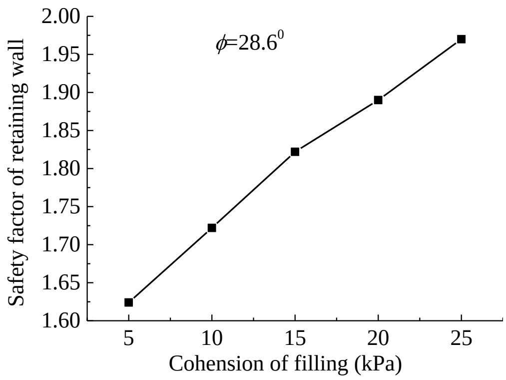


Fig. 13 Influence of cohesion of filling on safety factor of retaining wall

The safety factor of two-level stacked cantilever retaining wall F_s=1.74 is calculated by FEM. The influence of cohesion and internal friction angle of filling on the safety factor of retaining wall is shown in Fig. 13 and Fig. 14, respectively. It can be seen that the safety factor of retaining wall increases with the increase of cohesion or internal friction angle of filling soil. Higher strength soil should be selected as backfill in engineering practice, and the compaction degree should meet the requirements.

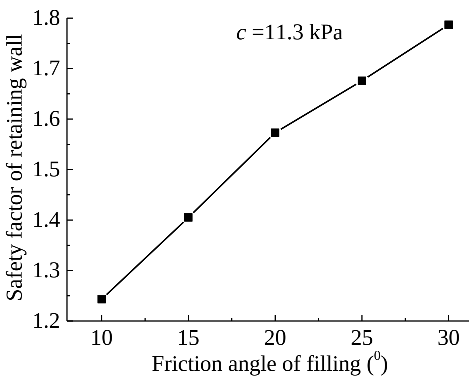


Fig. 14 Influence of internal friction angle of filling on safety factor of retaining wall

3 Conclusions

(1) The maximum lateral displacement of the two-stage stacked cantilever retaining wall filling occurs near the top of the upper wall. The lateral displacement of the fill in the lower part of the upper wall develops toward the free surface, and the lateral displacement of the fill near the top of the upper wall develops toward the

opposite direction.

(2) For there is no strong connection between the upper wall and the lower wall, the upper wall and the lower wall show different movement trends. The lower wall has the tendency of overturning to the empty surface, while the upper wall rotates away from the empty surface with the displacement of the fill.

(3) The vertical earth pressure acting on the heel plate of the upper wall and the lower wall presents non-linear characteristics. The closer to the wall root, the smaller the vertical earth pressure is. The farther away from the wall root, the greater the vertical earth pressure. The vertical earth pressure of the heel plate of the upper wall is greater than that of the overlying soil, and the maximum vertical earth pressure of the heel plate of the lower wall is basically the same as that of the overlying soil at that position.

(4) The lateral earth pressure on the back of the upper wall and the lower wall presents non-linear characteristics. The distribution of the lateral earth pressure on the back of the upper wall is similar to that of the traditional single cantilever retaining wall. The rigid heel plate of the upper wall is pressed on the top of the lower wall filling, which results in the larger lateral earth pressure on the top of the lower wall.

(5) When the two-level stacked cantilever retaining wall is unstable, there are two slip surfaces in the filling. The first slip surface runs through the filling based on the heel plate root of the lower wall, and the second slip surface runs through the upper filling based on the heel plate root of the upper wall.

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