



# Research on Improvement Calculation Method of Design Thrust of Anti Slide Pile

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**Abstract.** At present, based on the transfer coefficient method, most of the anti-slide pile design thrusts are calculated by the overload method and the strength reserve method respectively. Many algorithms only consider the remaining sliding force behind the pile and the safety factor that meets the requirements of the design conditions. Generally, the safety factor is the safety factor of the sliding slope behind the pile after the anti slide pile is reinforced. For the entire landslide, there are two safety factors before and after the pile, which is not the design safety factor target value, and there is a big difference between the safety factor and the treatment goal required by the specification. Through the study of the pile-soil interaction of anti-slide piles, it is believed that in addition to the active residual sliding force transmitted by the blocks behind the pile, the anti-slide piles are simultaneously subjected to the passive residual anti-sliding force transmitted upwards by the blocks in front of the pile. The stress analysis shows that: Firstly, according to the different active and passive properties of anti-sliding force transmission and sliding force transmission, the mechanical model of anti-sliding force transmission is studied, and the calculation formula of anti-sliding force transmission coefficient is derived; Secondly, It is believed that the anti-slide pile provides horizontal thrust to the landslide, and two components of the sliding surface direction and the vertical sliding surface direction are generated. The balance equation is established and the overload method and the strength reserve method of anti-slide pile thrust calculation formula are derived; Thirdly, according to the principle of setting piles in the anti-slip section, the optimal location of anti-slide piles are proposed; Fourthly, after verification of cases, the safety factors before and after the piles calculated by the overload method are basically equal, and consistent with the design safety factors. Calculation result shows that the strength reserve method to calculate the safety factor before the pile is accurate and reliable, and the result of the safety factor behind the pile is relatively small.

**Keywords:** Anti-sliding pile · Design thrust · Anti-sliding force transmission coefficient · Location selection condition · Safety factor

## 1 Introduction

In recent years, China has carried out large-scale construction of infrastructure projects such as highways, water conservancy and railways. During the construction process,

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engineering excavation was carried out near the foot of the hillslope, resulting in a decrease in the shear resistance of the lower part of the slope. Sliding outside could cause landslide hazard and directly threaten project construction and the service capacity after construction. In terms of landslide treatment, if more anti-slide piles are placed in the position of the shear outlet, it will directly affect the space of other engineering construction. Therefore, the anti-slide piles arranged in the anti-slip section are usually selected as an effective method. This retaining structure is in the form and widely used, which has little impact on the construction site and can ensure that the slope is in a safe and stable state within the design period in the future. Because the anti-slide pile is subjected to the combined effect of the landslide thrust in front of the pile and the soil resistance behind the pile, the pile-soil relationship is complicated. The calculation methods of design thrust of anti-slide piles are diverse, and the results are quite different. At present, most of them are calculated according to the cantilever anti-slide pile thrust at the shear outlet, which affects the accuracy of the anti-slide pile design technical index, such as the bending moment, shear force, section size, length of the anti-slide pile. The anchorage depth of the anti-slide pile in the stable soil below the sliding surface layer is also influenced. Different design methods effect the difficulty of the anti-slide pile construction and the engineering cost. Therefore, it is worthy of further study the calculation method of the anti-slide pile thrust.

Many experts have proposed different calculation methods for the design thrust of anti-slide piles, and the calculation results of each method are quite different. T.Ito (1981) [1] and Reese (1992) etc. [2] respectively proposed to calculate the anti-sliding force of anti-sliding piles under design conditions which based on Fellenius's Swedish section method and simplified Bishop method. S. Zeng, R. Liang [3] (2002) and the design code for anti-slide pile reinforcement of landslides by the Ohio Department of Transportation (GB7: Drilled Shaft Landslide Stabilization Design 2014) [4, 5] puts forward a calculation formula to calculate the lateral load of piles, which is similar to the commonly used transfer coefficient method in China and proves the scientificity and applicability of the transfer coefficient method to calculate the anti-slide pile thrust. Recently, many domestic experts and scholars have applied the idea of transfer coefficient to carry out a lot of research work on the calculation of the anti-slide pile thrust based on the overload method and the strength reserve method. According to the sliding force curve between the engineering design state and the benchmark working condition, Wang Liangqing (2005) et al. [6] chooses the smaller sliding force as the anti-slide pile thrust. Although this method highlights the economics of anti-slide pile design, it just considered the horizontal component of the remaining sliding force of the anti-slide pile, which induced the result of horizontal thrust calculation is too large. Zheng Yingren (2006) et al. [7] proposed that the landslide thrust should be calculated with the strength reserve, but the calculation of the anti-slide pile thrust was not further clarified. Although He Haifang et al. (2008) [8] considered the anti-sliding effect of the anti-slip section at the front edge of the slope, but it did not consider the transmission of the landslide resistance to the rock and soil in front of the pile through the supporting pile. There is a certain discrepancy between thrust calculation and actual thrust. Hu Mingjun et al. (2011) [9] proposed that the anti-slide pile can be directly installed at the shear exit, and the residual

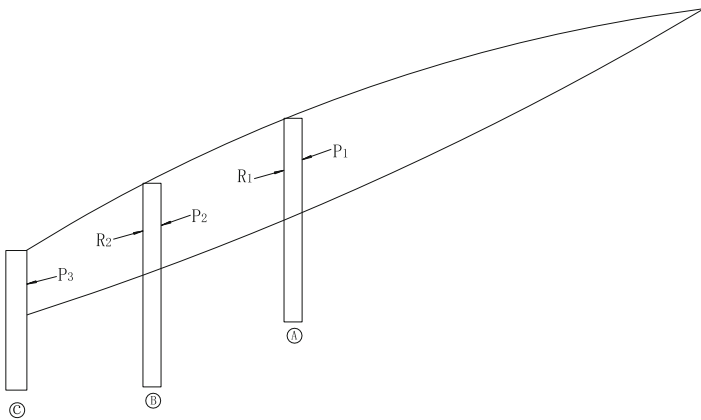
sliding force of the shear exit can be used as the design thrust of the anti-slide pile by loading back pressure. However, in reality many landslide shear exits are not stabilized. It may be necessary to install other engineering facilities, so loading back pressure and laying anti-slide piles have certain limitations in space. Based on the design thrust is equal to the difference between the two calculated values in the horizontal projection, Wang Peiyong (2010) et al. [10] utilized the overload method to calculate the remaining sliding force and the remaining anti-sliding force of the slope, and the design thrust on the contact surface of each block of the slope body is obtained. It is unreasonable to use the sliding force calculation method for the anti-sliding force transmission. The design specification was promulgated in 2015 [11] and the design thrust was calculated by multiplying by  $\cos\theta$  to the above two calculated landslide thrust, but it is not actually the design thrust of the anti-slide pile. According to transfer coefficient strength reserve method, Zhao Shangyi et al. [12] further studied that the horizontal reaction force of the anti-slide pile. The horizontal reaction force was added to the load system of the bar, and then the sliding surface was adjusted according to the design safety factor. The strength parameters were reduced so that the remaining sliding force of the last bar was exactly equal to 0. Li Huanhuan [13] further studied the algorithms of the overload method and the strength reserve method, and only the anti-sliding and anti-sliding effect of the anti-sliding pile were studied systematically. Zhao Shangyi et al. and Li Huanhuan did not consider the effect of the remaining anti-sliding force in front of the pile.

Based on the above, the anti-slide pile is simultaneously affected by the remaining sliding force behind the pile and the anti-sliding force in front of pile. At present, many algorithms only consider the remaining sliding force behind the pile and meet the safety factor required by the design conditions, usually referred to as the safety factor. There are two safety factors for the landslide before and after the pile for the entire landslide, which is not the target value of the design safety factor, and the safety factor required by the code and various technical standards is quite different. Through the principle of landslide section division, the authors use the transfer coefficient method to study the overload method and the strength reserve method based on the above-mentioned problem, and further improves the transfer coefficient overload method and the strength reserve method to calculate the horizontal thrust of the anti-slide pile.

## 2 Pile-Soil Interaction of Anti-slide Pile

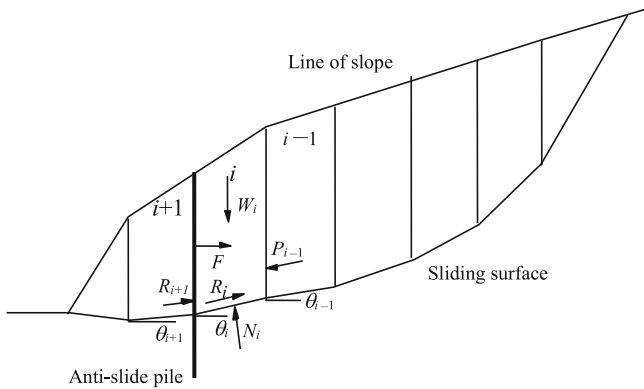
For the design of landslide anti-slide piles, the design position of anti-slide piles is usually selected in the anti-slide section, and its position selection has a greater influence on the effect of pile-soil, and ultimately affects the issue of whether the safety factors of the two parts of the slope are the same before and after the pile. Due to the different nature of the front and rear forces of the pile, there is a residual sliding force along the sliding surface behind the pile, and there is a residual anti-sliding force in front of the pile along the sliding surface in front of the pile. The residual sliding force is usually active under the action of gravity. The direction is always along the sliding surface, and the remaining anti-sliding force only shows up when the sliding force acts. The anti-sliding force has a passive nature. Both of these two force transmission processes have distinct active and

passive characteristics. It is concluded that there are three possible working conditions for the front and rear effects of the pile (see Fig. 1). In the first case, the anti-slide pile is set at A, and the remaining sliding force  $P_1$  behind the pile and the remaining anti-sliding force  $R_1$  in the landslide part in front of the pile are safe. The safety factor is greater than 1 and less than the design safety factor, indicating that this is the sliding section and is not the best position, and the anti-slide pile needs to be moved down to B; In the second case, the anti-slide pile is set at B which locates at the anti-slide section. The safety factor of the landslide part is greater than or equal to the design safety factor. In addition to the residual sliding force  $P_2$  after the pile, there is also a residual anti-sliding force  $R_2$  in front of the pile along the sliding surface. When the anti-slide pile is designed, the remaining anti-sliding force in front of the pile and the remaining sliding force behind the pile must be considered, which can meet the same safety factor before and after the pile to ensure the uniqueness of the safety factor of the landslide. In the third case, the anti-slide pile is set at C. The anti-sliding force in front of the pile is zero, and the safety factor is zero. Only the remaining sliding force  $P_3$  after the existing pile can be considered. Ultimately, it can also ensure that the overall landslide safety factor reaches the design safety factor and is unique. According to above, the second and third case are the best location for anti-slide pile treatment. From the study of anti-slide pile horizontal thrust, it is more reasonable to start with the calculation of residual sliding force and residual anti-sliding force. Based on overload method and strength reserve method, the following part will follow the idea of transmission coefficients method to study the calculation method of residual sliding force and residual anti-sliding force respectively.



**Fig. 1.** Three working condition of fore-and-aft action of piles

### 3 Transmission Coefficients Method



**Fig. 2.** Landslide block model

#### 3.1 The Assumption of Transmission Coefficients Method

The transfer coefficient method is a common method for calculating the remaining sliding force and stability of a landslide for a broken line sliding surface or a complex sliding surface that combines a circular arc and a broken line. This method is widely used in roads, railways, water conservancy, land and other industries. The calculation of the transfer coefficient method has the following six assumptions [14] (see Fig. 2):

- (1) The problem of landslide stability is regarded as a plane strain problem.
- (2) The sliding force is dominated by the shear stress parallel to the sliding surface and the normal stress perpendicular to the sliding surface, and the stress is concentrated on the sliding surface.
- (3) Regarding the landslide body as an ideal rigid plastic material, it is believed that the landslide body will not undergo any deformation during the entire loading process. Once the shear stress along the sliding surface reaches its shear strength, the landslide body begins to produce shear deformation along the sliding surface.
- (4) The failure of the sliding surface obeys the Mohr Coulomb failure criterion.
- (5) The direction of the remaining sliding force is consistent with the inclination angle of the sliding surface, and the difference between adjacent inclination angles is less than  $10^\circ$ . When it is a negative value, the remaining sliding force transmitted is 0.
- (6) The static balance condition is satisfied along the entire sliding surface, but the moment balance condition is not satisfied.

### 3.2 Overload Method and Strength Reserve Method to Calculate the Remaining Sliding Force Calculation Formula

The overload method calculates the remaining sliding force, mainly by multiplying the remaining sliding force of each block by the design working condition safety factor  $K_s$ , increasing the sliding force of each block, and its anti-sliding force remains unchanged, and calculating the remaining sliding force.

$$P_i = K_s T_i - R_i + P_{i-1} \psi_{i-1} \tag{1}$$

$$T_i = W_i \sin \theta_i \tag{2}$$

$$R_i = W_i \cos \theta_i \tan \phi_i + c_i L_i \tag{3}$$

$$\psi_{i-1} = \cos(\theta_{i-1} - \theta_i) - \sin(\theta_{i-1} - \theta_i) \tan \phi_i \tag{4}$$

Similarly, the strength reserve method calculates the remaining sliding force, which is mainly to divide the anti-sliding force of each block by the preset safety factor  $K_s$ . The anti-sliding force of each block is reduced by  $K_s$  times, and its sliding force remains unchanged.

$$P_i = T_i - R_i / K_s + P_{i-1} \psi_{i-1} \tag{5}$$

$$\psi_{i-1} = \cos(\theta_{i-1} - \theta_i) - \sin(\theta_{i-1} - \theta_i) \tan \phi_i / K_s \tag{6}$$

$P_i$  and  $P_{i-1}$  are the remaining sliding force (kN) of the  $i$ -th and  $i - 1$ -th sliding bodies, respectively, and when  $P_i < 0$  ( $i < n$ )  $P_i$  equals 0;  $F$  are the design values of the horizontal landslide thrust per linear meter, assuming the anti-slide pile is arranged on the left side of the first block;  $W_i$  is the self-weight per unit width of the  $i$ -th block (kN/m);  $c_i$  is the cohesive force of the block along the sliding surface (kPa);  $\phi_i$  is the  $i$ -th block The internal friction angle along the sliding surface ( $^\circ$ );  $\theta_i$  is the angle between the bottom surface of the first sliding body and the horizontal plane ( $^\circ$ );  $L_i$  is the length of the first sliding body along the sliding surface (m);  $E_n = 0$  is the first block to the first calculation block The transfer coefficient;  $K_S$  is the safety factor of the landslide anti-sliding design.

### 3.3 Derivation of the Residual Anti-sliding Force Calculation Formulae by the Overload Method and the Strength Reserve Method

When the force is transmitted in a landslide, most of them only consider the sliding force actively transmitted from the top of the slope to the shear outlet at the bottom of the slope, ignoring the anti-sliding force generated by the sliding surface that is passively transferred from the shear outlet at the bottom of the slope to the top of the slope. If the sliding force of each block is greater than the anti-sliding force in the sliding section, it indicates that the anti-sliding force provided by the block itself can not meet the sliding

force of the block, and the active residual sliding force will be generated; In the anti-slip section, the sliding force of each block is less than or equal to the anti-slip force. At the same time, the remaining anti-slip force transmitted along the sliding surface and in the opposite direction prevents the block from sliding down. This anti-slip force is only sliding It only manifests passively when the force is applied.

Calculation idea: When the remaining sliding force of the first block is actively transmitted downwards, at the same time the first block produces a thrust to the first block that transmits upwards along the sliding surface. This thrust is the remaining anti-sliding force passively generated by the first block. The direction of the remaining sliding force on the contact surface of the bars is not on the same straight line as the remaining sliding force of the first bar, and the included angle is the difference between the inclination angles of two adjacent bars (see Fig. 3).

Remaining anti-sliding force calculation steps: the calculation sequence is opposite to the remaining sliding force direction, then the calculation is calculated from the toe to the top of the slope sequentially along the sliding surface, and the anti-sliding force direction is consistent with the inclination of the sliding surface until the remaining sliding force is 0, indicating Just in the critical state.

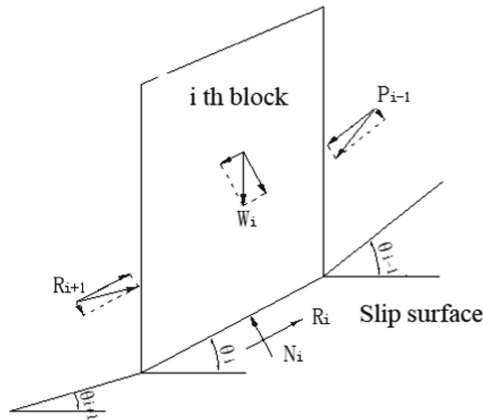


Fig. 3. Calculation model of residual sliding force of block

According to the force model in Fig. 3, the remaining sliding force transmission coefficient  $\psi_{i-1}$  is not the same as the remaining anti-sliding force coefficient  $\psi'_{i+1}$ . It can be seen from the landslide section that the difference between the two blocks is mainly due to the two different directions of transmitting the remaining force. In the process, the inclination angle  $\theta_i$  is usually larger than  $\theta_{i+1}$ . Therefore, when each bar transmits force, it is not in the same direction, and there are force components in other directions. When the residual anti-slip force of the  $i + 1$ th block is transmitted along the sliding surface to the  $i$  block, it is composed of two component forces, one of which is the same as the normal direction compressive stress on the sliding surface of the  $i$ th block to produce frictional resistance, and the other is divided into The force

direction is upwards along the sliding surface, and the two components play an anti-sliding effect. Therefore, the residual anti-sliding force transfer coefficient is the sum of the two component directions. Similarly, it can be known that the remaining sliding force is the  $i - 1$ th to the  $i$ th. When the bars are transmitted, the direction of the force component of the  $i - 1$ th bar is perpendicular to the direction of the sliding surface to generate friction to reduce the sliding force, and the remaining anti-sliding force transmission coefficient is the difference between the two components.

$$R'_i = W_i \cos \theta_i \tan \phi_i + c_i L_i - W_i \sin \theta_i + R_{i+1} (\cos(\theta_i - \theta_{i+1}) + \sin(\theta_i - \theta_{i+1}) \tan \phi_i) \tag{7}$$

According to (1) and (2), we can get

$$R'_i = R_i - T_i + R_{i+1} \psi'_i \tag{8}$$

$$\psi'_{i+1} = \cos(\theta_i - \theta_{i+1}) + \sin(\theta_i - \theta_{i+1}) \tan \phi_i \tag{9}$$

According to the overload method, the calculation of the remaining anti-sliding force also increases the sliding force of the bar by  $K_s$  times, and the calculation formula is:

$$R'_i = R_i - K_s T_i + R_{i+1} \psi'_{i+1} \tag{10}$$

$$\psi'_{i+1} = \cos(\theta_i - \theta_{i+1}) + \sin(\theta_i - \theta_{i+1}) \tan \phi_i \tag{11}$$

According to the strength reserve method, the calculation of the remaining anti-sliding force also only reduces the anti-sliding force of the block by  $K_s$  times, and the calculation formula is:

$$R'_i = R_i / K_s - T_i + R_{i+1} \psi'_{i+1} \tag{12}$$

$$\psi'_{i+1} = \cos(\theta_i - \theta_{i+1}) + \sin(\theta_i - \theta_{i+1}) \tan \phi_i / K_s \tag{13}$$

$R'_i$  represents the residual anti-skid force;  $\psi'_{i+1}$  is the residual anti-sliding force transmission coefficient of the  $i$ -th block.

Based on the above formula, it can be seen that the residual anti-sliding force transmission and the remaining sliding force transmission coefficient of the landslide resistance section are completely different, indicating that the overload method and the strength reserve method are used to calculate the remaining anti-sliding force using the original residual sliding force transmission coefficient calculation formula.

#### 4 Improved Calculation Method of Anti-slide Pile Thrust

The key to the thrust of the anti-slide pile is the choice of the position of the anti-slide pile. Usually choose the anti-slip section, and the best position must be the ratio of the remaining anti-slip force and the remaining sliding force before the pile of the anti-slip section is equal to the design safety factor, in order to ensure that the overall landslide



meets the design safety factor requirements. Under normal circumstances, the remaining sliding force behind the pile is provided by the thrust provided by the pile to meet the design safety factor, and at the same time it is appropriate to ensure that the remaining sliding force in front of the pile is greater than or equal to the safety factor of the design working condition. The main action of the pile is used for the front block of the pile. At this time, the anti-sliding force of the front block of the pile is used for the anti-slide pile, and the force system of the anti-slide pile system (see Fig. 4).

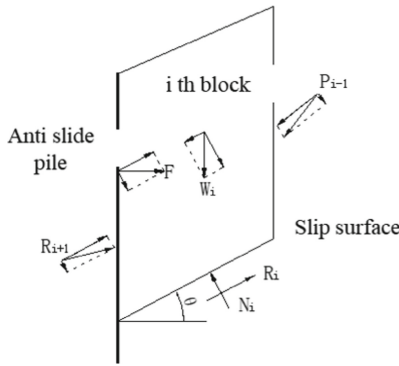


Fig. 4. Stress model between anti-slide pile and bar

The anti-slide pile is not only affected by the remaining sliding force transmitted downward from the back of the pile, but also by the remaining anti-sliding force transmitted upward from the front of the pile. When calculating the horizontal thrust of the anti-slide pile as the resultant force, it can be decomposed into two forces in the direction of the sliding surface and the normal direction of the sliding surface (see Fig. 4). The normal balance equation of the sliding surface of the block and the normal balance equation of the sliding surface are established to solve the problem. Two thrust calculation formulas are deduced separately: overload method and strength reserve method.

$$R_{i+1} \cos(\theta_i - \theta_{i+1}) + F \cos \theta_i + N_i \tan \phi_i + c_i L_i = W_i \sin \theta_i + P_{i-1} \cos(\theta_{i-1} - \theta_i) \tag{14}$$

$$R_{i+1} \sin(\theta_i - \theta_{i+1}) + F \sin \theta_i + W_i \cos \theta_i + P_{i-1} \sin(\theta_{i-1} - \theta_i) = N_i \tag{15}$$

It is obtained by combining the two Eqs. (14) and (15),

$$F = \frac{W_i \sin \theta_i - W_i \cos \theta_i \tan \phi_i - c_i L_i}{\cos \theta_i + \sin \theta_i \tan \phi_i} + \frac{P_{i-1} (\cos(\theta_{i-1} - \theta_i) - \sin(\theta_{i-1} - \theta_i) \tan \phi_i)}{\cos \theta_i + \sin \theta_i \tan \phi_i} - \frac{R_{i+1} (\cos(\theta_i - \theta_{i+1}) + \sin(\theta_i - \theta_{i+1}))}{\cos \theta_i + \sin \theta_i \tan \phi_i} \tag{16}$$

Substituting (2) from (3) and (9) into the calculation formula for the horizontal thrust of the anti-slide pile under the reference condition is

$$F = \frac{T_i - R_i + P_{i-1} \psi_i - R_{i+1} \psi'_{i+1}}{\cos \theta_i + \sin \theta_i \tan \phi_i} \tag{17}$$

In the same way, the calculation formula for the horizontal thrust of the overload method anti-slide pile under the design conditions is

$$F = \frac{K_s T_i - R_i + P_{i-1} \psi_i - R_{i+1} \psi'_{i+1}}{\cos \theta_i + \sin \theta_i \tan \phi_i} \tag{18}$$

Similarly, the formula for calculating the horizontal thrust of the anti-slide pile by the strength reserve method under the design conditions is

$$F = \frac{T_i - R_i / K_s + P_{i-1} \psi_i - R_{i+1} \psi'_{i+1}}{\cos \theta_i + \sin \theta_i \tan \phi_i / K_s} \tag{19}$$

When the residual anti-skid force is equal to zero by the three calculation formulas (17), (18) and (19), it is the second case. It can be seen that the horizontal thrust of the anti-slide pile is simply the horizontal component of the residual sliding force, and the horizontal projection of the residual sliding force difference between the design conditions and the reference conditions is not reasonable, but is related to the design safety factor. The transfer coefficient of the remaining sliding force behind the pile, the transfer coefficient of the remaining anti-sliding force in front of the pile, the horizontal angle of the sliding surface where the pile is installed and other factors are related.

After the slope is reinforced, it is verified whether the safety factor of the entire landslide is equal to the safety factor of the design working condition. According to the definition of “anti-sliding force/sliding force = safety factor”, according to the force system (see Fig. 3), the anti-slide pile is used as the reference point. The anti-sliding force is composed of the two forces vectorized by the anti-sliding force of all the bars and the horizontal thrust of the anti-slide pile. The sliding force is vectorized by the sliding force of all the bars. The formula for calculating the safety factor after the pile (20) and Calculation formula of safety factor in front of pile (21)

$$K_h = \frac{R_i + F_i \cos \theta_i + R_{i+1} \psi'_{i+1} + F_i \sin \theta_i \tan \phi}{T_i} \tag{20}$$

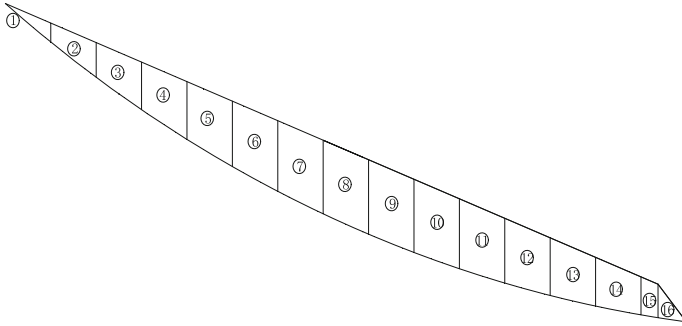
$$K_q = \frac{\sum_{i+1}^n (W_i \sin \theta_i \tan \phi_i + c_i L_i) - R_{i+1} \psi'_{i+1}}{\sum_{i+1}^n W_i \cos \theta_i} \tag{21}$$

$K_q$  is the calculated safety factor,  $T_i$  is the remaining sliding force of the  $i$ -th block,  $R_i$  is the remaining anti-sliding force of the  $i$ -th block,  $F_i$  is the horizontal thrust of the anti-slide pile at the  $i$ -th block,  $\psi'_{i+1}$  is the transfer coefficient of the residual anti-sliding force at the  $i + 1$ -th block,  $\psi_{i+1}$  is the first The remaining sliding force transmission coefficient at the  $i + 1$ -th block.

## 5 Case Study

Project overview: The landslide is an accumulation layer landslide, the roadbed is located at the front edge of the landslide, the anti-slide pile is located on the inner side of

the roadbed, and above the sliding surface is humus soil and silty clay soil with a small amount of gravel,  $\gamma_1 = 16.8 \text{ kN/m}^3$ ,  $\Phi_1 = 16.2^\circ$ ,  $C = 9.6 \text{ kPa}$ . Below the slip surface is Neogene sandy mudstone. According to the terrain conditions and slip surface conditions, 16 blocks are divided, and the angle difference between the blocks is less than  $10^\circ$ . The landslide section is shown in Fig. 5 and Table 1.



**Fig. 5.** Landslide calculation section

According to the actual example, the two remaining sliding forces of overload method and strength reserve method are calculated respectively. The safety factor of the selected design working condition for landslide treatment is 1.2, regardless of whether the overload method or the strength reserve method is adopted. As can be seen from Fig. 6, Article 12 to Article 16. If the block safety factor is greater than 1.2, anti-slide piles can be deployed, which can not only meet the anti-slide pile supporting effect, but also meet the safety factor of the design working condition for the blocks in front of the pile.

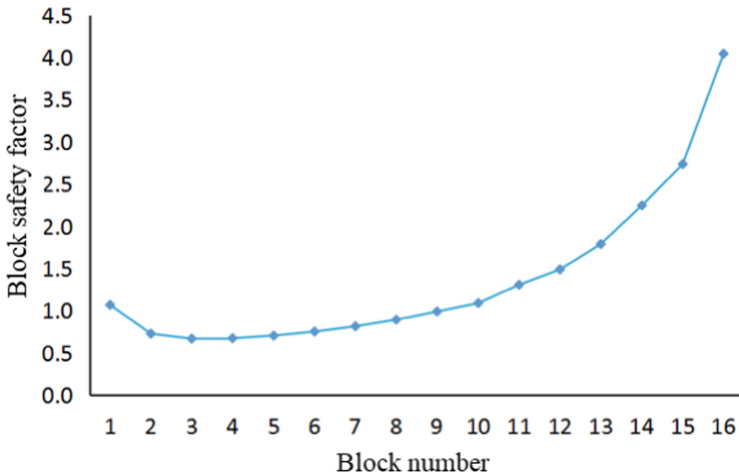
Table 2 is a comparison of calculation results obtained by various design thrust methods using the overload method. According to Table 2, it can be seen that Li Huanhuan's method, design code method, Wang Qingliang's method and the method in this paper are the same as those calculated by Li Huanhuan's method when anti-slide piles are installed at the exit of the landslide. The anti-skid force is 0, and the other calculated values are large, the maximum difference is 16%.

Table 3 is a comparison of calculation results obtained by various design thrust methods using the strength reserve method. According to Table 3, it can be seen that the design code method, Zhao Shangyi's method, Wang Qingliang's method, Wang Peiyong's method and the method in this paper are basically the same as those calculated by Wang Peiyong's method when anti-slide piles are installed at the landslide shear exit. The main reason is that the horizontal angle difference between the bars is small, which can be ignored. The numerical values of the design code method, Zhao Shangyi method, and Wang Liangqing method are quite different.

Analysis of the reason for the calculation difference: Zhao Shangyi's method did not consider the residual anti-sliding force, the lower block anti-sliding force of the anti-slip section was relatively large, and the design code method did not consider the residual anti-sliding force and the horizontal thrust of the anti-slide pile on the second block behind the pile. The friction caused by the positive pressure on the sliding surface, Wang

**Table 1.** Main geotechnical mechanical parameters

Block No	Volumetric weight $\gamma_i$ (kN/m <sup>3</sup> )	Force of cohesion $C_i$ (kpa)	Friction angle $\varphi_i$ (°)	Length of sliding surface $L_i$ (m)	Inclination angle of slip surface $\alpha_i$ (°)	Weight of block $Q_i$ (KN)
1	16.8	9.6	15.9	9.9429	41.4	195.2
2	16.8	9.6	15.9	9.6624	34.1	553.2
3	16.8	9.6	15.9	9.4196	31.9	848.8
4	16.8	9.6	15.9	9.2074	29.7	1086.5
5	16.8	9.6	15.9	9.0214	27.5	1270.3
6	16.8	9.6	15.9	8.8578	25.4	1403.3
7	16.8	9.6	15.9	8.7141	23.4	1488.2
8	16.8	9.6	15.9	8.5877	21.3	1527.5
9	16.8	9.6	15.9	8.4770	19.3	1522.9
10	16.8	9.6	15.9	8.3976	17.7	1480.2
11	16.8	9.6	15.9	8.2815	15.0	1392.9
12	16.8	9.6	15.9	8.2246	13.4	1262.3
13	16.8	9.6	15.9	8.1637	11.5	1097.1
14	16.8	9.6	15.9	8.1131	9.6	894.4
15	16.8	9.6	15.9	3.0346	8.3	276.8
16	16.8	9.6	15.9	5.0465	7.3	216.2



**Fig. 6.** Safety factors for each block

Liangqing’s method did not consider the friction caused by the positive pressure on the sliding surface of the first block in front of the pile. The remaining sliding force transfer coefficient is calculated. The difference in the inclination angle of the sliding surface of the main slip resistance section of the slope is small, and the difference in the two transfer coefficients is small.

**Table 2.** Comparison of results

Block no	Proposed method (KN)	Li Huanhuan method (KN)	Difference %	Design code method (KN)	Difference %	Wang Liangqing method (KN)	Difference %
12	1075.6	1489.5	38.5%	984.9	-8.4%	1012.6	-5.9%
13	1065.6	1353.6	27.0%	1024.8	-3.8%	1045.8	-1.9%
14	1057.8	1193.8	12.9%	1050.0	-0.7%	1064.8	0.7%
15	1053.8	1129.8	7.2%	1054.3	0.0%	1065.4	1.1%
16	1051.2	1051.2	0.0%	1056.8	0.5%	1065.4	1.4%

Note: The block number refers to the location of the anti-slide pile, as shown in Fig. 5.

**Table 3.** Comparison of results

Block no	Proposed method (KN)	Design code method (KN)	Difference %	Zhao Shangyi method (KN)	Difference %	Wang Liangqing method (KN)	Difference %	Wang Peiyong method (KN)	Difference %
12	912.5	1263.2	38%			771.9	-15%	844.1	-7.5%
13	904.3	1156.0	28%			831.3	-8%	795.3	-12.1%
14	897.8	1024.6	14%			880.5	-2%	764.4	-14.9%
15	894.5	971.8	9%			893.7	0%	839.6	-6.1%
16	892.3	905.1	1%	892.3	0	908.5	2%	824.6	-7.6%

Notes: 1. The Li Huanhuan method is the same as the Zhao Shangyi method in the strength reserve method, which only satisfies the calculation of the anti-slide pile at the shear exit. 2. The comparison results are based on the results of proposed method in this paper

Substituting the calculation results into Eqs. (19) and (20) to verify the safety factor. From the comparison results in Table 4, it can be seen that the safety factor after overloading method piles is basically equal to the safety factor of 1.2, and the safety factor after strength reserve method is less than or equal to 1.2. And there is a big difference. The calculation results of the first two methods of the pile show that the safety factor is 1.2. It can be seen that the calculation of the overload method is more accurate and reliable, and the safety factor before and after the pile is consistent.

**Table 4.** Comparison of factor of safety.

Block number	Overload method				Strength reserve method			
	After pile	Difference %	Before pile	Difference %	After pile	Difference %	Before pile	Difference %
12	1.21	0.83	1.2	0	1.2	0	1.2	0
13	1.21	0.83	1.2	0	1.19	0.83	1.2	0
14	1.2	0	1.2	0	1.18	1.67	1.2	0
15	1.2	0	1.2	0	1.18	1.67	1.2	0
16	1.2	0	1.2	0	1.17	2.50	1.2	0

## 6 Conclusion

Using the idea of transfer coefficient method, the two methods of overload method and strength reserve method are studied, and the following conclusions are drawn:

- (1) When studying the calculation of anti-slide pile thrust, in addition to the remaining sliding force behind the pile, the remaining anti-sliding force in front of the pile must also be considered.
- (2) The calculation formula of the anti-skid force transfer coefficient and the calculation formula of the remaining anti-skid force are proposed and deduced.
- (3) Considering the remaining sliding force before the pile and the remaining sliding force behind the pile at the same time, the calculation method of the anti-slide pile thrust is improved, and the optimal position selection condition of the anti-slide pile is proposed.
- (4) It has been verified that this method uses the overload method to calculate the safety factor before and after the pile is basically the same, and is consistent with the design safety factor. The strength reserve method calculates the safety factor before the pile is accurate and reliable, but the result of the safety factor behind the pile is relatively small.

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