Rock and Soil Mechanics

Volume 41 | Issue 2 Article 11

9-27-2020

Design and numerical analyses of high-fill slope strengthened by frame with prestressed anchor-plates

Yan-peng ZHU
Western Center of Disaster Mitigation in Civil Engineering, Ministry of Education, Lanzhou University of Technology, Lanzhou, Gansu 730050, China

Jun TAO
Western Center of Disaster Mitigation in Civil Engineering, Ministry of Education, Lanzhou University of Technology, Lanzhou, Gansu 730050, China

Xiao-hui YANG
Western Center of Disaster Mitigation in Civil Engineering, Ministry of Education, Lanzhou University of Technology, Lanzhou, Gansu 730050, China

Jun-guo PENG
Western Center of Disaster Mitigation in Civil Engineering, Ministry of Education, Lanzhou University of Technology, Lanzhou, Gansu 730050, China

See next page for additional authors

Custom Citation
ZHU Yan-peng, TAO Jun, YANG Xiao-hui, PENG Jun-guo, WU Qiang, . Design and numerical analyses of high-fill slope strengthened by frame with prestressed anchor-plates[J]. Rock and Soil Mechanics, 2020, 41(2): 612-623.

Design and numerical analyses of high-fill slope strengthened by frame with prestressed anchor-plates

Authors

Yan-peng ZHU, Jun TAO, Xiao-hui YANG, Jun-guo PENG, and Qiang WU

Rock and Soil Mechanics 2020 41(2): 612–623 ISSN 1000–7598
https: //doi.org/10.16285/j.rsm.2019.5035 rocksoilmech.researchcommons.org/journal

Design and numerical analyses of high-fill slope strengthened by frame with prestressed anchor-plates

ZHU Yan-peng[1, 2], TAO Jun[1, 2], YANG Xiao-hui[1, 2], PENG Jun-guo[1, 2], WU Qiang[1, 2]

1. Key Laboratory of Disaster Mitigation in Civil Engineering of Gansu Province, Lanzhou University of Technology, Lanzhou, Gansu 730050, China
2. Western Center of Disaster Mitigation in Civil Engineering, Ministry of Education, Lanzhou University of Technology, Lanzhou, Gansu 730050, China

Abstract: Plenty of high-fill slopes need to be strengthened in engineering projects in the mountainous area of the northwestern district of China with complex geological conditions. To provide sufficient anchoring force to fill slopes and to ensure their stabilities, we put forward a new structure of safety, stability, economy and convenience, named frame with prestressed anchor-plates, which suits for reinforcing the slopes with large fill, and whose reinforcement effect is great. Based on the limit equilibrium theory, we proposed the formula for pull-out resistance and the checking calculation method for the stability. Finite element analysis software PLAXIS 3D was applied to compare and verify the results of the proposed method. The displacement of the slope and the internal forces of a column in the frame are further analyzed, which explains the rationality of the results of numerical simulation, and proves that the frame with prestressed anchor-plates is effective for strengthening the slope and limiting the displacement by comparing with the displacement data of a slope project. By analyzing the variation of axial force and frictional strength during the process of construction, the working mechanism between the plates and the soil is exposed, and the influence of the prestress on the structure is explored. The analysis results can guide the design of high-fill slopes strengthened by the frame with prestressed anchor-plates.

Keywords: high-fill slope; ultimate pull-out resistance; stability; a new supporting and retaining structure; PLAXIS 3D

1 Introduction

It is often required to reinforce the slopes for the construction of various kinds of infrastructures. The commonly used supporting structures include gravity retaining wall, buttress retaining wall, cantilever retaining wall, anchor retaining wall, prestressed anchor (cable), anti-slide pile, pile plate retaining wall, reinforced earth retaining wall, anchor plate retaining wall, and soil nail wall[1–3]. Based on the different treatment methods to natural soil, the slopes have two different types, i.e., excavation slope and fill slope.

The structural forms suitable for reinforcing the fill slope include gravity retaining wall, counterfort retaining wall, cantilever retaining wall, reinforced earth retaining wall, anchor plate retaining wall, anti-slide pile, and pile plate retaining wall. In these structural forms, the gravity retaining wall, cantilever retaining wall and counterfort retaining wall cannot be used to reinforce the soil slope whose height is over 10 meters[1], because they are difficult to meet the requirements for anti-overturning stability. According to the specification[2], the maximum cantilever height of piles for pile plate retaining wall can reach 15 m. If a cantilever is higher, the pile will have larger cross-sectional area, larger depth and greater displacement of pile top. Due to the inability of graded reinforcement, using pile retaining wall to reinforce the high fill slope usually has a high cost, and the same applies to the cantilevered pile. Through case study, Jia et al.[4] concluded that reinforced soil slope has the advantages of easy construction, fast progress and less land occupation, and thus is better than gravity retaining wall. Reinforced earth retaining wall is commonly used in fill slope with flat terrain and sufficient reinforcement space[5]. Although the reinforced earth retaining wall can be used in high fill slope and is easy to construct, it couldn't keep the same geometric form with the frame prestressed anchor rod (cable) or pile sheet wall prestressed anchor rod (cable) in the area where excavation section and filling section are interlaced.

Anchor plate retaining wall is a light retaining structure suitable for fill slope, with a height less than 6 m for single-stage design and less than 10 m for double-stage design[6]. Applying prestress on the anchor plate is necessary to control the displacement of the reinforced slope. Because the anchor plate is buried vertically in the soil, the process of prestressing may easily cause a new potential fracture surface along the anchor plate surface in the deep layer of the soil. So far, the anchor plate retaining walls used in engineering projects have rarely used prestress. To strictly control the displacement of slope, the anchor plate can be combined with other rigid structures. A popular composite structure is the prestressed cantilever retaining wall. Zhang et al.[7] investigated the

Received: 8 January 2019 Revised: 31 May 2019
This work was supported by the Major Special Science and Technology Project of Gansu Province (1302FKDA030) and the Program for Changjiang Scholars and Innovative Research Team in University of Ministry of Education of China (IRT_17R51).
First author: ZHU Yan-peng, male, born in 1960, Master, Professor, mainly engaged in the teaching and research of retaining structure, ground treatment, engineering accident analysis and treatment. E-mail: zhuyp@lut.cn

composite structure of anchor plate and cantilever retaining wall through a laboratory model test and numerical simulation, and discussed the mechanical performance of prestressed anchor plate retaining wall. Zhu et al.[8] used high-strength prestressed anchor cable and reinforced concrete horizontal reinforcement plate to improve the support system of anchor plate wall, and analyzed the stability of this improved system, and the result shows that the improved system performed well. However, compared with the light supporting structure, the above-mentioned composite structure is complicated to build, expensive and somewhat cumbersome.

Prestressed anchor (cable) frame beam, as a lightweight and flexible retaining structure, is easy to construct and requires slight excavation, small masonry, and short construction period, and can effectively improve the slope stability, and, in addition, can be combined with other protective measures, and thus is becoming more and more popular in engineering practice[9]. However, under the limitation of construction technology and cost, the ultimate anchorage strength of the anchorage section and the fill soil is low for prestressed anchor (cable) frame beam when it is used to reinforce the fill slope, and thus it is difficult to satisfy the overall stability requirement of the slope.

To overcome the above-mentioned problems, Zhu et al.[10] invented a new type of retaining structure, i.e., prestressed anchor plate, which is specially designed for the fill slope. This structure can not only provide enough pullout resistance in the fill soil to meet the stability requirements, but also can be directly installed on the surface of the fill soil such that the drilling grouting process is omitted. Because of these advantages, this new method has been used in lots of slope supporting engineering projects successfully. This new retaining structure can be combined with the concrete frame grid structure system, which can not only omit the processes of drilling, grouting and others, but also can apply prestress to control the slope displacement. Meanwhile, this new retaining structure can partly resist the vertical displacement of the fill slope due to its high stiffness. However, no available design method and stability checking model of this new retaining structure existed.

This paper presents a method to get the pullout resistance and analyze the stability for the new retaining structure. Based on the finite element analysis software, a numerical model is conducted for the slope strengthened by the frame prestressed anchor plate. Using the numerical model, the displacement of the slope, the shear force of the frame column, the shear stress and axial force distribution on the surface of the anchor plate are analyzed, respectively. The finite element strength reduction method is used to verify the shear strength calculation method in the pullout resistance calculation formula. The regularity of the stress distribution in the frame prestressed anchor plate is summarized, which can provide a reference for the design and research of the frame prestressed anchor plate supporting structure in the fill slope.

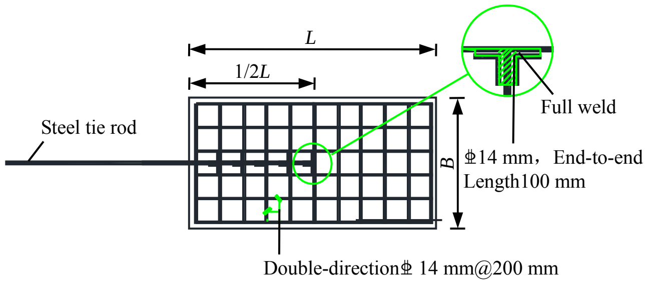


Fig.1 Diagram of an anchor-plate

2 Design and calculation theory for anchor plate

2.1 Basic structure of anchor plate

Figure 1 shows the configuration of the anchor plate, which consists of reinforced concrete prefabricated plates and tie rods. The internal reinforcing bar of reinforced concrete precast plates and the tie rods are welded by angle steel. The anchor plate body is embedded in the stable area of filling soil outside the most dangerous slip surface.The anchor plate is connected to the frame lattice beam-column node through a tie rod. When the earth pressure acts on the concrete frame system, the frame lattice will transmit the external force to the anchor plate through the tie rods, and thus slope stability is improved by the pullout resistance provided by the anchor plate. Therefore, the earth pressure produced by the slope is carried by the columns, beams and prestressed anchor plates jointly. The connecting structure of the tie rod, anchor plate and concrete frame is presented in Fig.2.

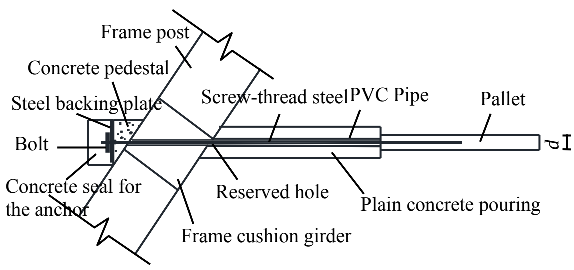


Fig.2 Working diagram of the anchor-plate system

2.2 Calculation formula of anchor plate pullout resistance

The forces on the anchor plate are presented in Fig. 3, and the ultimate pullout resistance T_u presented in Fig. 3 can be expressed as:

$$T_u = \min\{T_s, T_p\} \tag{1}$$

where T_s ($= f_y A_s$) is the limit tensile force of the reinforcing bar; f_y is the yield strength of the reinforcing bar; A_s is the steel cross-sectional area; T_p is the ultimate value of pullout resistance for an anchor. From Eq. (1) we know that increasing the values of T_s and T_p can increase the T_u value. Since the T_s value can be easily increased by increasing the yield strength f_y of the reinforcing bar or increasing the cross-sectional area of the reinforcing bar, we focus on increasing the T_p value. The anchor plate, as a reinforced concrete prefabricated plate, has sufficient tensile strength, and therefore the instability of the slope is caused by the insufficient friction between the anchor plate and the soil, which causes a relatively large displacement between the anchor plate and the surrounding soil, and as a result, the anchor plate is pulled out of the soil. The pull-out resistance provided by the anchor pallet is composed of the friction between the pallet and the soil and the passive earth pressure on the compression surface of the pallet:

$$T_p = 2F + Q \tag{2}$$

where F is the frictional resistance between the anchor plate and the soil; Q is the passive earth pressure on the side where the anchor plate is connected to the tie rod, and can be expressed as follows:

$$Q = \sigma_p A_d = K_p \gamma h A_d \tag{3}$$

where A_d is the side surface area of the anchor plate (m^2); h is the cover thickness of the stratum above the anchor plate (m); γ is the unit weight of the soil layer around the anchor plate (kN/m^3); $K_p = \tan^2(45° + \varphi/2)$ is the Coulomb passive earth pressure coefficient of the soil around the anchor plate.

The friction F between the anchor plate and the soil can be obtained by the following equation

$$F = \tau A_f \tag{4}$$

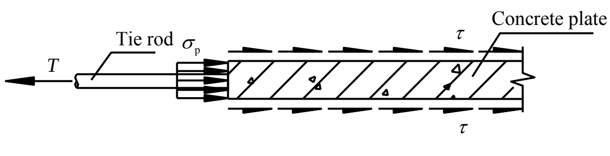


Fig.3 The force diagram of an anchor-plate

where τ is the shear strength of the interface between the anchor plate and the soil; A_f (m^2) is the contact area between the anchor plate and the soil, namely the area of the upside or downside surface of the anchor plate.

The shear strength of the interface between the anchor plate and the soil can be obtained by the following equation:

$$\tau = \mu(\sigma + \sum\Delta\sigma) \tag{5}$$

where σ ($= \gamma h$) is the self-weight vertical stress of the soil (kPa); $\sum\Delta\sigma$ is the vertical additional stress caused by the overload; μ is the friction coefficient between the anchor plate and the surrounding soil, which can be obtained through experiment. The recommended value for μ in loess is ranging from 0.3 to 0.4.

Engineers choose to increase the length instead of diameter for the anchoring section to increase the of the anchor rod (cable) due to the limitation of the construction technology and cost. However, increase the length may be also limited by these two factors. From Eqs. (1) to (5) we can get that the pull-out resistance of anchor plate in soil can be easily improved by increasing its thickness, width and length. In addition, the anchor plate saves the processes of drilling, grouting and others, which results in simple construction, low cost and environmental friendliness.

2.3 Checking calculation of global stability of slope reinforced by frame prestressed anchor plate

Several slope stability analysis methods, including the Swedish arc method, Bishop slice method, Janbu slice method, unbalanced thrust transfer coefficient method and finite element method, are frequently used to find the sliding surface. According to the specification[1], circular sliding method can be used to analyze the stability of soil slope or large-scale rock slope with cataclastic structure. Based on the limit equilibrium theory and the failure mode of circular sliding, and utilizing the idea of slice method, we can establish the safety factor calculation model for the anti-sliding stability of the slope reinforced by the frame prestressed anchor plate structure. Based on Fig.4, the stability coefficient for any arc sliding surface can be obtained as follows:

$$K_{SF} = \frac{M_R}{M_S} \tag{6}$$

where M_S is the sum of the sliding moments on the sliding surface, and can be expressed as

$$M_S = \left[df \sum_{i=1}^{n} (w_i + q_0 b) \sin\theta_i \right] R \tag{7}$$

where M_R is the sum of the anti-sliding moments on the sliding surface, which is mainly provided by the cohesion and friction of the soil, the pull-out force of the anchor plate and the horizontal thrust of the bottom structure of the frame (such as anti-slide piles).

$$M_R = \left[\sum_{i=1}^{n} c_i l_i d + d \sum_{i=1}^{n} (w_i + q_0 b) \cos\theta_i \tan\varphi_i \right] R + \sum_{j=1}^{m} T_{uj} \left[\cos\theta_j + 0.5 \sin\theta_j \tan\varphi_j \right] R + P(Y + H) \tag{8}$$

where n is the number of slices of the sliding soil mass; m is the number of layers of the anchor plate; f is the importance coefficient of the supporting structure; w_i is the weight of the i th soil slice; q_0 is the surcharge load on the slope top; b is the width of the soil slice; c_i is the standard value of the cohesion at the slip surface of the i th soil slice; φ_i is the standard value of the internal friction angle of the soil at the slip surface of the i th soil slice; φ_j is the standard value of the internal friction angle of the soil at the intersection of the horizontal line of the jth layer anchor plate and the slip surface; θ_i is the angle between the tangent line of the ith slip surface and the horizontal plane; θ_j is the angle between the tangent line and the horizontal plane at the intersection of the jth layer anchor plate and the slip surface; l_i is the arc length of the ith slip surface; d is the thickness of sliding soil mass; R is the radius of the arc; P is the design value of the horizontal thrust of the frame's bottom structure; H is the support height of the slope; Y is the vertical distance from the center of the sliding surface to the top of the slope; T_{uj} is the ultimate pullout resistance of the jth layer anchor plate outside the circular slip surface , which can be obtained by Eq. (1).

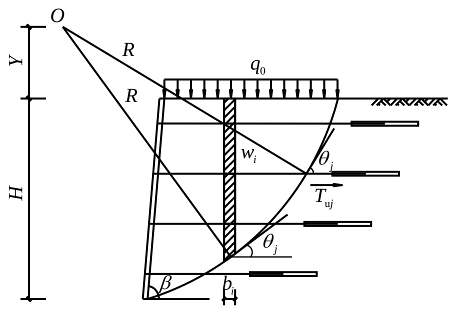


Fig.4 Checking calculation diagram for stability against slide of a frame with prestressed anchor-plates

The minimum K_{SF} value for multiple slip surfaces is the stability coefficient of the slope. The most dangerous slip surface and its circle center can be obtained by the analytical method or computer searching method.

The pullout resistance calculation formula for the new structure and the stability analysis model for the slope reinforced by this structure are presented above. Specifically, this new method considers the change in the frictional resistance with burial depth between the anchor plate and the soil, and the engineers can choose the appropriate size of the anchor plate during design. Therefore, this new method can be used for the reinforcement design of fill slope.

3 Finite element analysis

Using GeoStudio software, Ye et al. [11] analyzed the effect of frame prestressed anchor plate on the displacement and stability of high fill slope by treating anchor plate units as anchor rod units. To further analyze the working mechanism and characteristics of the anchor plate, and to verify the stability calculation formula of the anchor plate proposed in this paper, we use PLAXIS 3D finite element software to analyze the stability of the frame prestressed anchor plate reinforced slope in Baidaoping Shigou, Chengguan District, Lanzhou (more details introduced in section 3.2), including four fill slopes with slope ratio of 1:0.3, 1:0.5, 1:0.7 and 1:0.9, respectively.

3.1 Model establishment

The height and section width of the slope are both 12 m. The frame prestressed anchor plate structure is used to reinforce the slope. The spatial locations of the anchor plate and soil parameters for the four slopes are the same. The physical and mechanical parameters of the soil in each layer of the model slope are presented in Table 1 and are taken from the field data of the slope project in Baidaoping Shigou.

Divide the soil into layers and simulate the filling process through freezing and activating each soil layer. The effects of groundwater and seepage are ignored. The anchor rod of the anchor plate is simulated by a point-to-point anchor unit, and its material type is set to elastic. The length, width and thickness of anchor plate are 4 m, 1 m and 0.1 m, respectively. In PLAXIS 3D, the anchor plate is simulated by the plate element, the reinforcement is simulated by the point-to-point anchor element, and the reinforcement connected with the tie rod inside the plate body is simulated by the beam element. Proper meshing of the model is needed to extract the frictional resistance data of the anchor plate and create the positive and negative interfaces of the anchor plate. E_A of the reinforcing bar in anchor plate is set to 9 800 kN. The relevant parameters of the anchor plate in each layer are presented in Table 2. The layer numbers 1 to 4 represent the top layer to the bottom layer. The three-dimensional model is shown in Fig.5.

Table 1 Design parameters of the supporting structure

Soil type	Chosen model	Unit weight γ / (kN/m^3)	Elastic modulus E / MPa	Poisson's ratio	Cohesion c / kPa	Internal friction angle φ / (°)	Coefficient of friction μ	Surcharge load on the slope top / kPa
Fill soil	Mohr–Coulomb	16.5	35	0.25	20	24	0.4	0
Sandstone	Mohr–Coulomb	22.0	50	0.18	28	50	—	—

Table 2 Data of anchor-plates in each layer

Layer number	Length of tie rod / m	Relative height from ground / m	Prestress value / kN
1	12.5	10.5	60
2	12.0	7.5	90
3	9.5	4.5	120
4	8.0	1.5	160

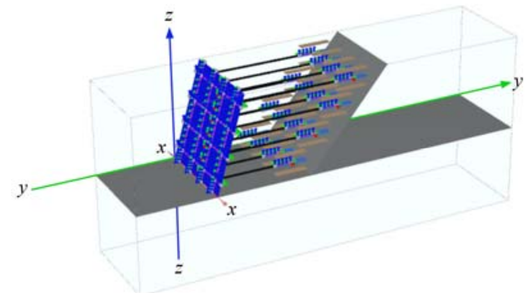


Fig.5 Three-dimensional model of the slope with a slope ratio of 1:0.3 (soil hidden)

Table 3 The comparison of safety factor

Slope ratio	K_{SF}		
	Method of this article	Method of finite element strength reduction	M-P Method
1:0.3	1.652	1.701	2.009
1:0.5	1.745	1.813	2.251
1:0.7	2.154	2.288	2.533
1:0.9	2.500	2.703	2.716

3.2 Comparison of stability calculation results

The finite element strength reduction method is used in PLAXIS 3D to calculate the safety factor for these four slopes. Table 3 shows the comparison of safety coefficients for the four slopes with different slope ratios for the proposed solution, Morgenstern-Price limit equilibrium method and the strength reduction method. In this section, $f = 1$, $n = 50$, $\mu = 0.4$ and $q_0 = 0$ kN/m. The Morgenstern-Price method uses the Slope calculation module in Geostudio software. The anchor plate is simulated by the "anchor" unit in the Geostudio software for the Morgenstern-Price method. The anchorage strength of each layer is obtained by Eq. (5). The anchor diameter is obtained by the conversion of the length of the anchor plate cross section. The Geostudio model for the slope with slope ratio of 1:0.3 is presented in Fig.6. The limit state displacement contour for the slope with slope ratio of 1:0.3 in PLAXIS 3D is presented in Fig. 7.

Table 3 indicates that the trends of these four K_{SF} values for the proposed solution, M-P method and finite element method are consistent. Same as the M-P method and the finite element method, the proposed method can also accurately evaluate the stability of the frame prestressed anchor plate reinforced slope. Because it is based on the limit equilibrium method, the method proposed in this paper is simple, fast and easy to use relative to the other two methods. Therefore, the method proposed in this paper can be used in the design of the frame prestressed anchor plate structure. The location and shape of the most dangerous slip surface (i.e., the dotted line in Fig.7) indicates that the assumption of slip surface arc passing through the slope toe in the slip surface search model is reasonable.

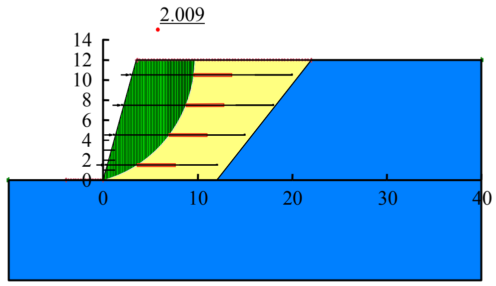


Fig.6 Calculation result using M-P method (unit: m)

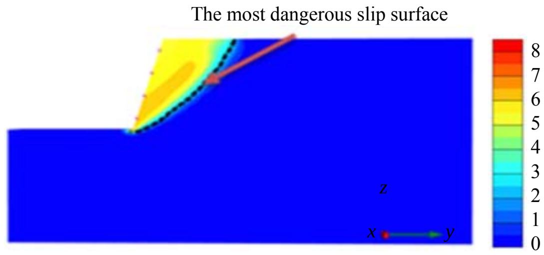


Fig.7 Displacement contour of the slope under limit state (unit: mm)

3.3 Slope displacement analysis

A displacement monitoring sensor was installed at the shoulder of the second-level slope to monitor the slope displacement in the Shigou slope project (see Fig.8). The design profile of Shigou slope and the location of monitoring points are presented in Fig.9 (by the time of reading the monitoring data, the third-level slope has not yet started soil filling). We choose the slope with 1:0.7 slope ratio (the same slope ratio with Shigou slope) in this paper to represent the Shigou slope and analyze its displacement.

Fig.8 Installation of displacement meter

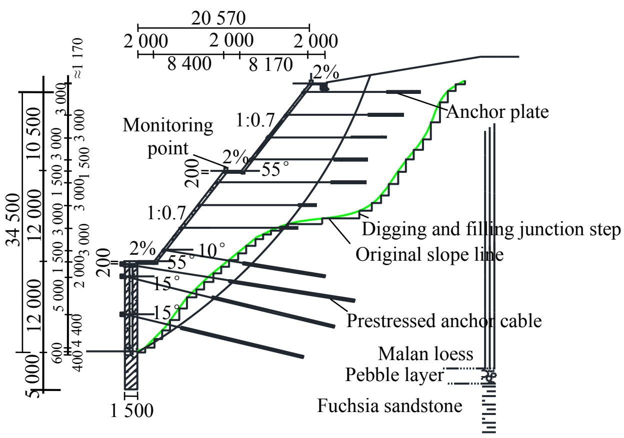


Fig.9 A profile of Shigou slope project (unit: mm)

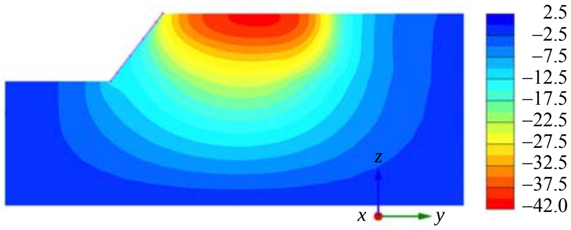


Fig.10 Vertical displacement contour of the slope (unit: mm)

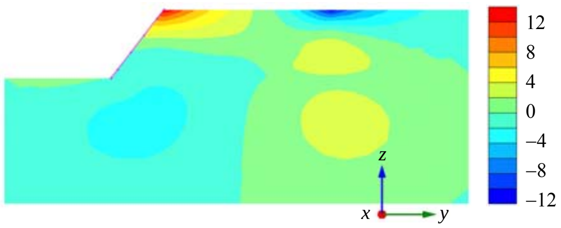


Fig.11 Horizontal displacement contour of the slope (unit: mm)

Figures 10 and 11 show the vertical and horizontal displacements of the slope model, respectively. Fig.10 indicates that the maximum vertical displacement occurs at a distance of about 5 m from the top to the shoulder of the slope, which is caused by the self-weight-induced 4 cm-settlement of the fill soil. Figure11 indicates that the maximum displacement (about 13 mm) in the horizontal direction of the slope occurs at two places, i.e., the shoulder of the slope top and far from the shoulder of the slope. After the maximum settlement occurs, the surrounding soil moves to the location of the maximum settlement and increases the horizontal displacement. Furthermore, the prestress applied on the anchor plate also increases inward horizontal displacement. Figure 11 also indicates that the frame prestressed anchor plate structure plays a good role in displacement control for this slope.

Figure 12 presents the change in the displacement of the Shigou slope shoulder after the construction of the second lift slope top. After the construction of the third lift slope, the slope shoulder also displaces towards the inner side of the slope, and the displacement of the shoulder slowly increases with time to about 22 mm. The monitored displacement value is about twice of the simulation value in Fig.10.

The monitoring data is the displacement of the second lift slope shoulder, which is 24 m high; while the simulation value is the horizontal displacement of the first lift slope shoulder, which is 12 m high. The simulated settlement value is lower than the monitored value, and the same is true for the horizontal displacement. Therefore, the simulated horizontal displacement is smaller than the monitored value. The consistent trend of the monitored and simulated horizontal displacements at slope shoulder indicates that the simulation results are correct. In the slope reinforced by frame prestressed anchor plate, compactness of each compacted soil layer should be ensured to minimize vertical displacement induced by consolidation settlement. Meanwhile, the role of prestressing should also be taken seriously.

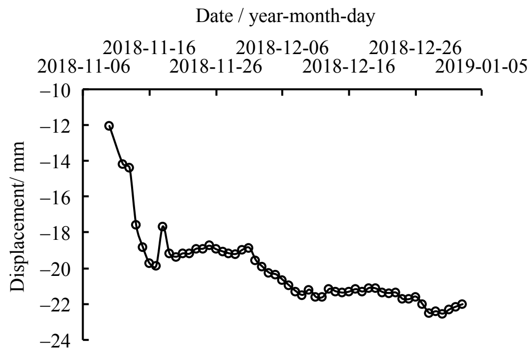


Fig.12 Monitoring values of horizontal displacement at the slope shoulder

3.4 Internal force analysis of slope frame columns

The earth pressure produced by the slope is carried by the frame system consisting of columns, beams and prestressed anchor plates. The earth pressure is transmitted to the anchor plate through the columns and beams, and then transmitted to the stable fill soil layer in the slope through the anchor plate. Therefore, columns and beams are mainly subjected to shear and bending moments. A column in the system of slope enforced by the frame prestressed anchor plate helps to connect the beam and fix the tie rod. The performance of the anchor plate in the slope with 1:0.3 slope ratio is analyzed through the shear and bending moment distribution curves of the frame column in this slope. Figures 13 and 14 present the shear diagram and bending moment diagram, respectively.

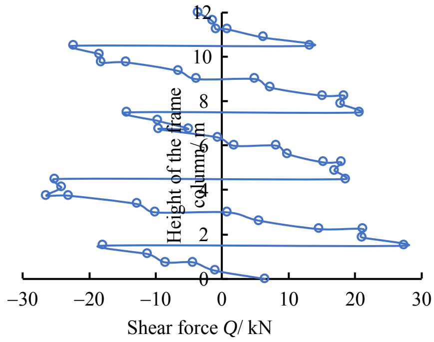


Fig.13 Shear force diagram of a column in the frame

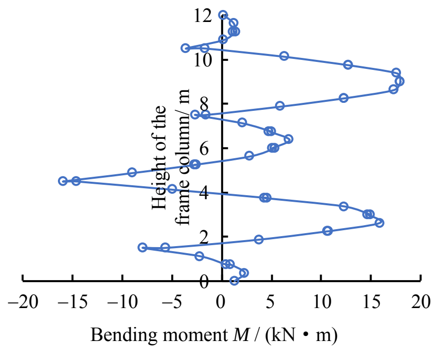


Fig.14 Bending moment diagram of a column in the frame

Figure 13 indicates that the shear force of the frame column increases gradually with increasing soil depth. A sharp decrease in shear force at the location of every anchor plate occurs and indicates that the anchor plate has a good anchoring effect on the slope. The sharp decreases in the shear force for the frame column at the location of each anchor plate from top to bottom are 35.6, 35.0, 43.7, and 45.4 kN, respectively. Fig. 14 shows that the bending moments of the frame columns alternate from positive to negative, with a maximum value of 18 kN•m, indicating that the anchor pallet can effectively prevent the bending moment from continuously increasing in one direction.

The prestressed anchor plate significantly reduces the stress on frame structure and effectively transfers the load of the whole structure to the deeper soil, which is consistent with the mechanism of the popular light flexible retaining structure. The frame structure is well combined and can increase the slope stability by reducing the slope displacement and the internal force of the frame structure.

3.5 Axial force of anchor plate

The anchor plates are arranged outside the potential dangerous slip surface in the fill soil to provide anchoring force from the deeper stable soil layer. The variation of the axial force for the bottom anchor plate during the construction process in the slope with 1:0.3 slope ratio is caculated using PLAXIS 3D, and is analyzed in this section. Figure 15 presents the axial force (for unit width of anchor plate, kN/m) for varying filling height at the time when the tension rod has not been prestressed.

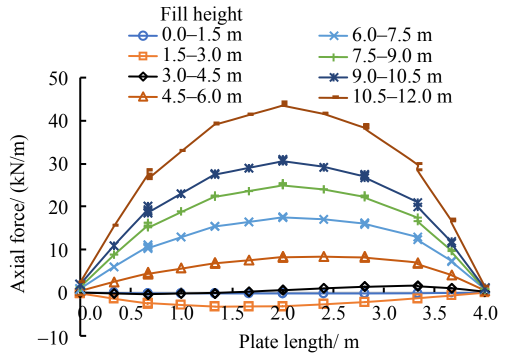


Fig.15 Variation of axial force of an anchor-plate in bottom layer during filling process

Figure 15 indicates that the curves of the axial force for anchor plate is parabola, with maximum value in the middle, which is similar to the curves of the axial force distribution of soil nails in soft rocks [12]. The initial axial force of anchor plate is 0. The axial force has no obvious change at the beginning of filling. When the height of fill soil reaches 1.5–3.0 m, the anchor plate becomes deformed owing to the fill soil, and thus the value of axial force changes to negative, which indicates that the anchor plate increases the rigidity of the slope against vertical deformation. After the height of fill soil becomes more than 3 m, the effect of earth pressure at the slope bottom on the anchor plate is greater than that of the fill soil self-weight induced pressure. The axial force of anchor plate increases with increasing earth pressure on the bottom retaining plate. The anchor plate produces maximum axial force in its middle location because the end of the reinforcing bar connected to the tie bar extends to half length of the anchor plate.

Figure 16 presents the axial force for the anchor plate versus the anchor plate length during the process of prestress application. The curves indicate that, with the increase in prestress, the increases in axial force is greater in the front part of anchor plate and smaller in the end part of anchor plate. The peak value occurs in the forefront part of the anchor plate. The front half of the anchor plate is subjected to a large axial force. The axial force of the anchor plate increases the stablity with increasing prestress. It is worth noting that, after the prestress is applied, the axial force of the anchor plate decreases suddenly at the location of about 0.65 m, and the decrease of value increases with increasing prestress.

The axial force of the anchor plate decreases from the front part to the back part, which indicates that the anchor plate can transfer the active earth pressure carried by the slope support structure to the stable deep soil layer. Figure17 presents the three-dimensional axial force distribution on the bottom anchor plate, and the other anchor plates have the same axial force distribution trend with the bottom one. The all positive values of axial force indicate that the axial forces are all tensile force. The maximum axial force occurs in the front part for all anchor plates.

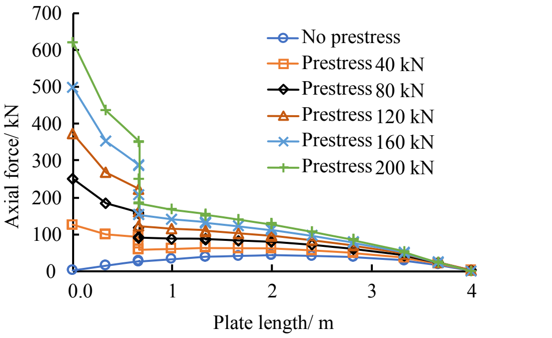
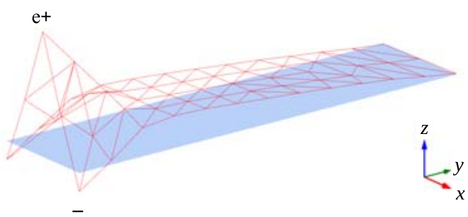


Fig.16 Variation of axial force of an anchor-plate in the bottom layer during adding prestress



Axial force N_2 (Magnified 2×10^{-3} times)
The maximum value = 557.9 kN / m (The node 41 285 in the element 740)
The minimum value = −83.02 kN / m (The node 41 287 in the element 737)

Fig.17 Axial force diagram of an anchor-plate in the bottom layer

The axial force decreasing sundenly at the location of 0.65 m, as presented in Fig. 16, because the tie rod of anchor plate enters half length of the concrete slab and is connected with its internal horizontal ribs of the plate through welding. The tie rod entering the concrete slab is reinforcing bar, which has bonding strength with concrete. The prestressing force on the tie rod is transmitted to the reinforcing bar in the concrete slab, and lead to deformation of the reinforcing bar, which would produce bonding strength with concrete and cause deformation of the concrete slab. The deformations of reinforcing bar and concrete slab are not consistent. The consistent deformations of reinforcing bar and concrete slab occur at the location of 0.65 m on the concrete slab, and the deformation of reinforcing bar is greater before 0.65 m, whereas that of concrete slab is greater after 0.65 m. The strain of the reinforcing bar decreases due to the bonding strength, while the deep concrete is pulled by the concrete in the width direction of the front two sides, which causes the strain of concrete larger than that of the reinforcing bar in the deep slab, and thus is constrained by the reinforcing bar.

3.6 Anchor plate frictional strength analysis

The average values of the frictional strength of every calculation element on each anchor plate for the slope with 1:0.3 slope ratio in PLAXIS 3D are compared with the results obtained by Eq.(5), in which $\mu = 0.3$ and 0.4, respectively. The comparisons are presented in Fig.18.

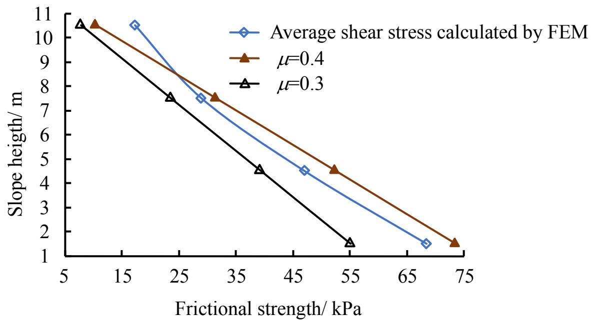


Fig.18 Comparison of calculated results of frictional strength

Figure 18 shows the values of frictional strength of the anchor plate calculated using finite element method. It is found that except for the top anchor plate, the calculated results of the other three layers are between those calculated by Eq. (5) (μ takes 0.3 and 0.4, respectively), which indicates that the proposed solution in this paper can reasonably reveal the fact that the frictional strength of the anchor plate increases with increasing anchor plate burying depth. The μ value should be determined through on-site pull tests.

Figure19 presents the frictional resistance of anchor plate for varying height of fill soil and indicates that the frictional resistance increases with increasing fill height. The neutral point for frictional resistance changing from positive to negative occurs at the location of 2 m on anchor plate. Once the fill height reaches over 3 m, the neutral point moves from 3.7 m to 1.6 m on the anchor plate.

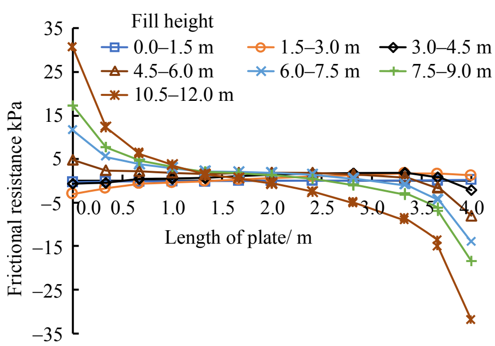


Fig.19 Variation of frictional strength with the fill height of an anchor-plate in bottom layer

The soil stress at the bottom of the slope and the sliding force of the slope both increase with increasing fill height.

Several potential sliding surfaces forms gradually during the filling process. The movement trend of the adjacent soil on both sides of the sliding surface is opposite. The sliding surface of the anchor plate produces a neutral point with alternating positive and negative frictional resistance. Figure 20 presents the movement trend of potential slip surface druing the filling process, which can be deduced from Figure 19. Figure 20 can explain the phenomenon in Figure15 that the axial force transfers from the edge to the middle of the anchor plate graudlly during the filling process. The area where the anchor plate is subjected to friction from sliding soil (the friction pushing the anchor plate out of the slope) is referred to as passive friction zone, and the area where the anchor plate is subjected to friction from stable soil (the friction from the surrounding stable soil due to the active outward movement trend of the anchor plate) is referred to as active friction zone. With the increase of fill height, the sliding surface passing through the bottom anchor plate moves gradually to the front part of the anchor plate, and then the passive friction zone becomes smaller and the active friction zone becomes larger. The side surfaces of the anchor plates are expected to be active friction zone, however, the side surfaces of the anchor plates always have passive friction zone before the prestress is applied.

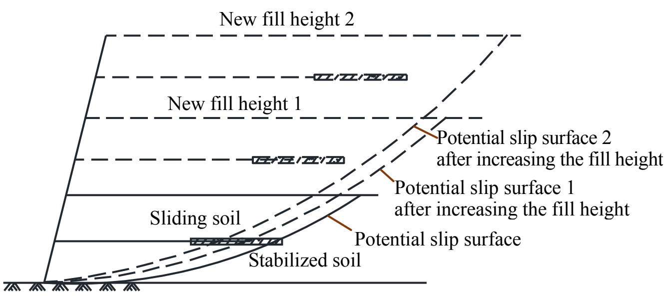


Fig.20 Change of potential slip surface with the fill height through the anchor-plate in the bottom layer

Figure 21 presents the frictional strength of the bottom anchor plate for varying prestress. It indicates that the frictional strength at the front part of the anchor plate decreases with increasing prestress, whereas the frictional strength at the back part of the anchor plate has a reverse trend, and the increase rate of the frictional strength at the back part of the anchor plate is smaller than the decrease rate of the frictional strength at the front part of the anchor plate. With the increase of prestress, the position of the neutral point with positive and negative alternation of frictional strength moves gradually from the back part to the front part of the anchor plate, namely, the passive friction zone decreases gradually, while the active friction zone increases gradually. When the prestressing force exceeds 120 kN, the passive friction zone disappears, and the side surface of anchor plate all becomes active friction zone, which provides the frictional resistance to prevent the soil from sliding out. According to Fig.19 and Fig.21, during the process of filling and prestress application, the potential slip surface of anchor plate moves gradually from the back part to the front part of the anchor plate. When the prestressing force reaches a certain value, the potential slip moves outside of the anchor plate. Therefore, to ensure sufficient active friction zone, the prestress applied in the bottom anchor plate should not be too small.

Figure 21 also indicates that the peak value of the frictional strength appears at the end part of the anchor plate, which means that the soil around the end part of the anchor plate is more stable. The frictional strength decreases suddenly at the location of 3.7 m on the anchor plate when the prestress increases to 160 kN. When the prestress is greater than 160 kN, the location of the frictional strength peak value changes from the end part to the 3.7 m of the anchor plate, and a sudden decrease of the frictional strength occurs at the locations before 2.8 m of the anchor plate.

The prestress will pull the anchor plate out of the slope. The stress caused by the friction force at the interface between the anchor plate and soil increases with increasing prestress, and once this stress increases to a certain value, the increase rate of frictional strength near the end part of the anchor plate decreases with increasing prestress. After the prestress exceeds 120 kN, a failure point appears at the interface between the anchor plate and soil, which leads to a sudden decrease of frictional strength at this point. With the increase of prestress, more failure points appear, and finally the frictional strength decreases suddenly at several points on the anchor plate. Therefore, the appropriate prestress helps to improve the soil state [13], but, the interface between the slab and soil will be damaged once the prestress is overloaded. Therefore, the prestress should be appropriate and should be graded (i.e., the prestress of the upper anchor plate is smaller than that of the lower part) in design.

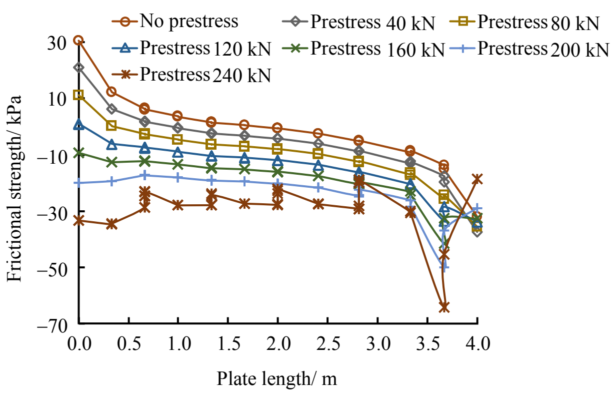


Fig.21 Frictional strength variation with the prestress of an anchor-plate in bottom layer

4 Application of anchor plate in engineering practice

We have many practical experiences in using the anchor plate in reinforced slope, and the stability of these reinforced slopes was improved significantly.

4.1 Zhangjiachuan slope support project

This project is located at Zhangjiachuan Residential District in Zhangjiachuan Hui Autonomous County, Tianshui City, Gansu Province. The heights of original rubble retaining walls around the building site range from 0.35 to 3.30 m. Because it's higher than the original outdoor ground, the proposed site needs to be filled. The slope heights after filling vary with the terrain and range from 2.61 to 7.21 m. To improve the stability of these slopes and reduce cost, we chose the frame prestressed anchor plate support structure to reinforce the slope. According to the *Technical Specifications for Building Slope Engineerin* (GB50330—2013) [1], the importance level of these slopes is Grade II, and the safety factor of these slopes is 1.0.

To reduce the engineering cost, the frame prestressed anchor plate structure was used on the top and outside of the existing gravel retaining wall. According to the site survey and geotechnical survey report of construction site, the design parameters are selected as shown in Table 4.

Table 4 Design parameters of the supporting structure in Zhangjiachuan slope

Soil type	Soil thick-ness / m	Unit weight γ /(kN/m^3)	Cohesion c / kPa	Internal friction angle φ / (°)	Coefficient of friction μ	Surcharge on the slope top / kPa
Backfill soil	>10	19	10.0	20	0.4 (Upper layer); 0.55 (Lower layer)	10

The anchor plates for these slopes have no more than two layers, with their lengths being 1, 2, 3 and 4 m. The width and thickness of these anchor plates are all 1 m and 80 mm, respectively, and the horizontal spacings are all 3 m. The prestress for these anchor plates is 60 kN. The vertical section and cross section for one reinforcement section are presented in Fig. 22 and Fig. 23, respectively. Compared with other sections, the lower anchor plate tie rod in the section presented in Fig. 23 is connected with the frame column crossing through the upper part of the rubble retaining wall, which significantly improves the anti-overturning stability of the rubble retaining wall. The project was completed in 2011, and the slope reinforcement structures still work well now.

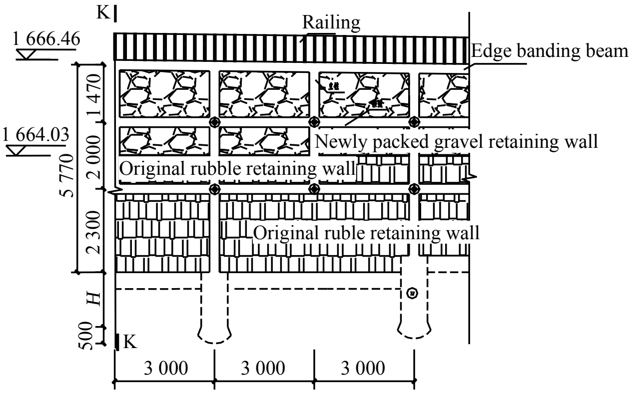


Fig.22 Elevation of a section in Zhangjiachuan slope project (unit: mm)

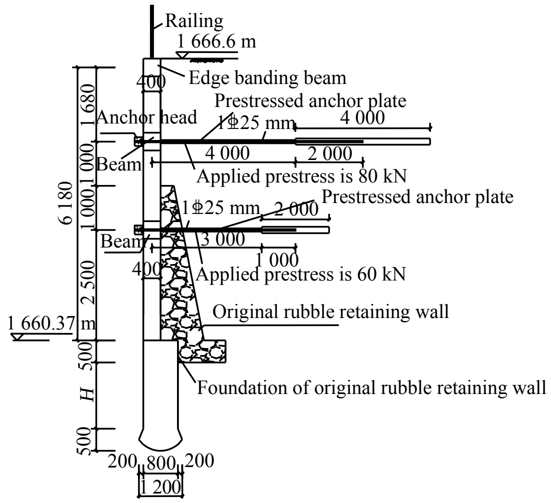


Fig.23 A profile in Zhangjiachuan slope project (unit: mm)

4.2 Lanzhou Baidaoping Shigou slope project

This project is located at Shidaogou, Baidaoping, Chengguan District, Lanzhou City, Gansu Province. The length of the unstable slope in this project is 700 m, and the height of the slope ranges from 21 m to 36 m. The terrain for this slope is complex, with multiple fold-line steep ridges and concave arc-shaped plane shapes, which is presented in Fig. 24.

Among these slopes, several of them had already slid, and many slopes did not meet the stability requirement, and should be reinforced. In order to expand the area for the resettlement of residents near the top of the slope, these slopes need to be filled. Reinforcement schemes are set to third or second level. The first level is 12 m high cast-in-place piles and prestressed anchor cable support; the second level over the first level has two options, one is frame prestressed anchor cables in the area with small fill soil volume and the other is frame prestressed anchor plate in the area with large fill soil volume. Therefore, the second level and third level supporting structure can keep consistent in appearance in the small fill soil area and the large fill soil area.

Fig.24 A section of Shigou unstable slope

The design parameters of the supporting structure are shown in Table 1. The slope reinforced by the second and third level supporting structure has 1:0.7 slope ratio and 3 m horizontal distance for anchor plate. The anchor plate size is 2 m × 1 m in the second level supporting structure and 4 m × 1 m in the third level supporting structure, and the thickness of the anchor plate is 100 mm for both supporting structures. The prestress for these anchor plates is 70 kN. Figure 9 presents the support structure arrangement in one cross section. Figure 25 presents the anchor plates used in the project. The exposed reinforcing rings on the anchor plate are convenient to hoist to the installation point.

Fig.25 The anchor-plates used in field

4.3 Longnan Wudu Dongjiang new district outer ring slope project

This project is located at Wudu District, Longnan City, Gansu Province, with a maximum slope height of 42 m. After the road completed construction, the slope became unstable due to disturbance by human activities. Ye et al. carried out reinforcement design and post-construction monitoring of the slope[11]. The filling material is composed of loess-like silty clay and pebble, with a mixing ratio of 2:8. Table 5 presents the physical and mechanical parameters for the supporting structure.

Table 5 The design parameters of the supporting structure

Soil type	Soil thickness / m	Unit weight γ /(kN/m^3)	Cohesion c / kPa	Internal friction angle φ / (°)	Coefficient of friction μ
Mixed filler	40	21	5	33	0.4

In this project, the size of the anchor plate is 3 m × 1 m and the thickness of the anchor plate is 80 mm. The highest part of the slope is reinforced in 4 levels, and the height of every level is 10 m. The supporting structure in the slope has four-layer anchor plates, and the prestress for these anchor plates is 30 kN. The slope ratio of this slope is 1:1. The design drawing of the cross section of the slope is presented in Fig. 26.

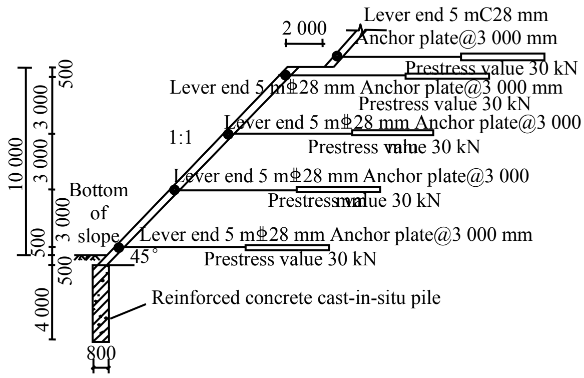


Fig.26 A profile of the slope project in Dongjiang New District, Longnan (unit: mm)

The horizontal displacement of the deep layer and the slope shoulder, and the earth pressure carried by the concrete frame were monitored during the construction of the supporting structure and after its completion. Figures 27 and 28 present the monitoring data given by Ye et al.[11]. Figure 27 shows the comparison results of the horizontal displacement at the place 1 m from the shoulder between monitoring data versus numerical simulation results, and indicates that the slope reinforced by the anchor plate effectively limits the horizontal displacement of the slope. Figure 28 presents the comparison of the earth pressure carried by the concrete frame between monitoring data versus numerical simulation results, and indicates that frame prestressed anchor plate structure can effectively reduce the earth pressure on the concrete frame. Detailed monitoring scheme and analysis of monitoring results were given in reference [11].

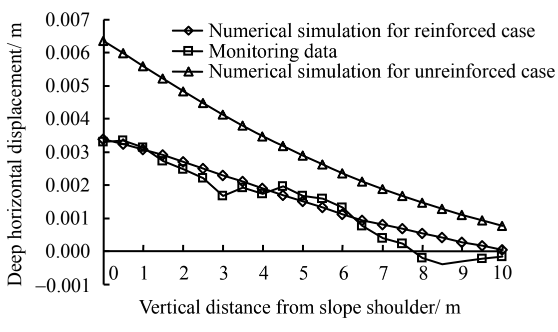


Fig.27 Comparison of deep horizontal displacements in the slope

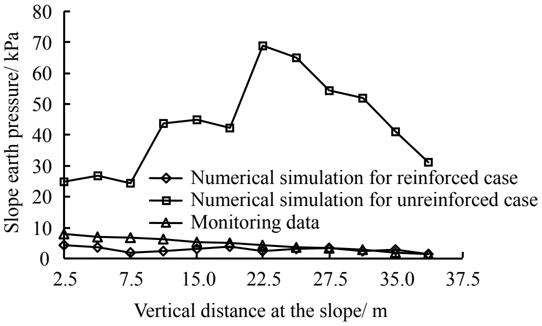


Fig.28 Earth pressures of slope surface

5 Conclusions

This paper presents a new structure, the frame prestressed anchor plate, to reinforce the fill slope. A method used to calculate the pullout resistance and analyze the stability for the new retaining structure was proposed. Based on a finite element analysis software, a numerical simulation was conducted to analyze the slope strengthened by the frame prestressed anchor plate. The main conclusions are as follows:

(1) The pullout resistance formula proposed in this paper can basically reflect the changing trend of the frictional strength of the anchor plate at different soil depths under the limit state. Once the value of μ is obtained through the pullout resistance test, this formula can be used in the design for anchor plate. The stability analysis method in this paper can be used to evaluate the stability of the slope reinforced by the frame prestressed anchor plate, and can be used in engineering practice.

(2) The simulations results indicate that the displacement and deformation of the slope reinforced by frame prestressed anchor plate structure are well controlled. Comparison between the monitoring data and numerical simulation results for the horizontal displacement of Grade 2 slope shoulder for Baidaoping Shigou slope in Lanzhou indicates that the numerical simulation results can well reflect the actual displacement. The distribution of shear forces and bending moments for the frame columns indicates that the prestressed anchor plate works well with the concrete frame, and has strong reinforcement efficacy.

(3) The PLAXIS 3D software was used to simulate the construction process, and the axial force of the anchor plate was analyzed. The change of the axial force and the sudden change of location during the prestress application reflect the deformation relationship between the internal reinforcing bar and the plate.

(4) Based on the PLAXIS 3D numerical model, the frictional strength of the anchor plate was analyzed. The concept of active friction zone and passive friction zone for the anchor plate was proposed. With the increase of fill height, the sliding surface passing through the bottom anchor plate moves gradually from the back part to the front part of the anchor plate. frictional strength.The change of frictional strength during the prestress application indicates that the prestress of the anchor plate should be neither too small nor too large.

This paper presented a method used to calculate the pullout resistance and analyze the stability for a new retaining structure, i.e., the frame prestressed anchor plate. The interaction mechanism between the anchor plate and the surrounding soil was also analyzed through PLAXIS 3D finite element software. Because it’s convenient and fast in construction and effective, this new structure has a good application prospect in fill slope engineering.

References

[1] Chongqing Urban Rural Construction Commission. GB 50330 — 2013 Technical code for building slope engineering[S]. Beijing: China Architecture & Building Press, 2013.

[2] The Second Railway Survey and Design Institute. TB 10025–2006 Code for design on retaining structures of railway subgrade[S]. Beijing: China Railway Publishing House, 2006.

[3] CCCC Second Highway Consultants Co., Ltd. JTG D30–2015 Specifications for design of highway subgrades[S]. Beijing: China Communications Press, 2015.

[4] JIA Bin, XU Chao, ZHOU Hua-dong. Study on the selection of fill slope protection scheme of a planning airport[C]//Proceedings of the 9th National Engineering Geology Congress. Qingdao: [s. n.], 2012: 179–185.

[5] HOU Jun-wei. Experimental study and numerical analysis for anchor rod retaining wall in filling area[D]. Chongqing: Chongqing University, 2010.

[6] LI Hai-guang. New retaining structure design and engineering examples[M]. Beijing: China Communication Press, 2010.

[7] ZHANG Hong-bo, XIE Quan-yi, YUE Hong-ya, et al. Mechanical performance of prestressed anchor plate retaining wall[J]. Journal of Shandong University (Engineering Science), 2016, 46(5): 95–101.

[8] ZHU Zhi-hua, KONG Suo-cai, WANG Hai-liang. A new type anchored retaining wall with anchor cable and reinforced plate[J]. Chinese Journal of Underground Space and Engineering, 2017, 13(Suppl.2): 771–776.

[9] CHENG Liang-kui. Research and new progress in ground anchorage[J]. Chinese Journal of Rock Mechanics and Engineering, 2005, 24(21): 5–13.

[10] ZHU Yan-peng, ZHU Sheng-xiang, YE Shuai-hua, et al. Flexible support system pile-wall with prestressed anchor-plate and construction method: 201510022317.X[P]. 2015-01-16.

[11] YE Shuai-hua, FANG Guang-wen, CHEN Chang-liu, et al. Numerical and monitoring analyses of new reinforcement technology of frame with prestressed anchor-plates in high fill slope and its application[J]. Chinese Journal of Geotechnical Engineering, 2018, 40(Suppl.1): 57–64.

[12] LOU Guo-chong, BU Jian-qing. Field monitoring of a high slope of weak rocks with soil-nailing support and determination of the slip surface[J]. China Civil Engineering Journal, 2005, 38(3): 106–109.

[13] WANG Deng-qun. Stability analysis of slope supported by anchor considering prestress[D]. Lanzhou: Lanzhou University of Technology, 2013.