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Characteristic analysis of the combined retaining structure of batter anchor pile and slide-resistant pile

Integrating the characteristics of two structures, the combined retaining structure of batter anchor piles and slid-resistant piles are applicable to high slope engineering with large horizontal load. This paper employs the finite element software ANSYS and the strength reduction method to explore how the various characteristic parameters of the structure, ranging from the inclination angle of the anchor pile, pile diameter, anchorage depth, to pile spacing, affect slope stability and load bearing properties of the structure. The analytic results show that: the inclination angle of the anchor pile should fall between 20° and 45°, the pile should be driven no less than 8m into the stable rock formation within the theoretical broken angle, but the distance should not be excessively deep, and the pile spacing should be 2~3 times the pile diameter.

Keywords: Batter anchor piles, combined retraining, characteristic parameter, finite element method, load bearing properties.

1. Introduction

Nowadays, the landslide is posing a great threat to the production, construction and life and property of our society. High slopes are particularly dangerous due to the severe damages brought by their severe deformation in the accident [1-4]. Typical high slopes like thick soil or high fill slopes often have large horizontal load, which brings forward strict requirements on slope treatment. The combined retaining structure of batter anchor pile and slide-resistant pile is an appropriate method for treating the slopes. Consisting of anchor piles and slide-resistant piles, the structure has both the ability to withstand huge horizontal load and certain resistance to vertical settlement. Despite its wide application to practical engineering, the combined retaining structure has not been extensively studied, especially on the load bearing properties reflected by specific characteristics. Targeted at the combined retaining structure of batter anchor pile and slide-resistant pile, this paper mainly explores how different characteristics of the structure affect the changing pattern of mechanical behaviours and slope stability, thereby providing some reference for the optimization of the structure. The characteristics include the inclination angle of the anchor pile, pile diameter, anchorage depth, and pile spacing. For this purpose, the author uses the numerical simulation software ANSYS to establish the 3D model of the combined slope retaining structure of batter anchor pile and slide-resistant pile, and compares and analyzes the different characteristic parameters of the structure based on the finite element strength reduction method. The findings of this paper are suitable for engineering practices.

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2. Calculation model and material parameters

The geometric dimensions of the slope model are shown in Fig.1. The slope is composed of a slip bed, a slip belt, and a slip mass, and retained by four sets of batter anchor pile and slide-resistant pile. The slip bed is a stable rock stratum, the slip belt is a 1 m thick weak sliding surface, and the soil slip mass is in the tendency of sliding downward under the dead weight. The anchor piles and slide-resistant piles are made of reinforced concrete. It is known that the section of each slide-resistant pile is a square of side length d_1 = 2 m and the length of each slide-resistant pile is h = 20 m. For each batter anchor pile, the shape parameters are configured as follows: sectional side length d_2, inclination angle *á*, anchorage depth *z*, and pile spacing *l*.

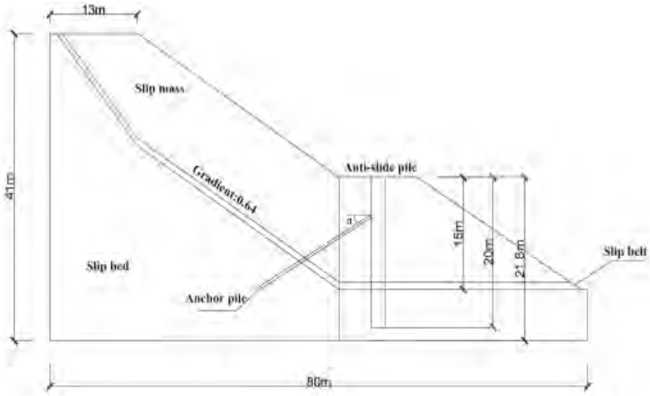


Fig.1 Model geometry

Table 1: Parameters of model materials

	Density ρ (kg/m^3)	Elastic modulus E (Pa)	Poisson ratio μ	Cohesion c (Pa)	Internal friction angle φ (°)
Slip mass	2 500	5.0×10^7	0.30	1.5×10^4	22.0
Slip bed	2 800	1.6×10^9	0.25	6.0×10^5	38.4
Slip belt	1 630	1.0×10^7	0.35	9.0×10^3	16.3
Pile in the structure	2 500	3.1×10^{10}	0.20	Designed with elastic materials	

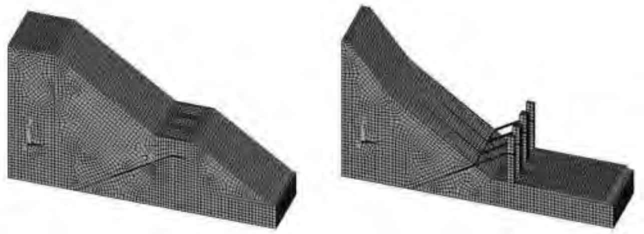


Fig.2 Finite element analysis model

The 3D numerical model is established by ANSYS (Figure 2). The entity unit SOLID45 is selected to simulate the piles and soil, and the contact between pile and soil are simulated with the contact units TARGE170 and CONTA174. In reference to previous research results and in light of the engineering practices, the author lists the material parameters in Table 1 [5-7] and designs the piles with elastic materials.

3. Strength reduction method

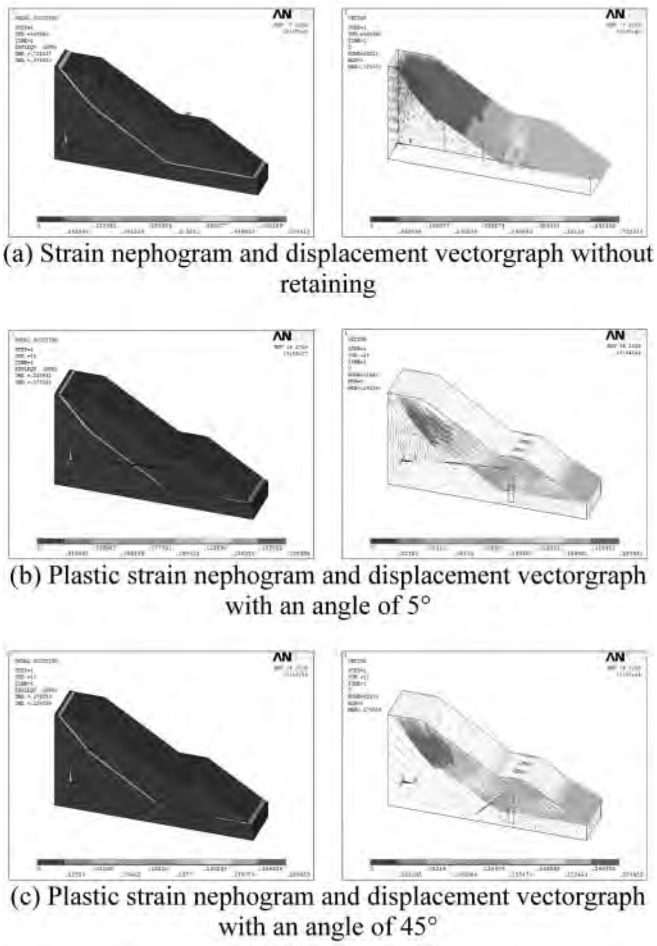
In order to determine slope stability by the finite element strength reduction method, [8-9] the slip belt soil parameters (*c* and φ) should be reduced before being substituted into the operations. In addition, the reduced parameters should also be converted to yield criterion [10] before being applied to numerical simulation because only the Drucker-Prager criterion of ANSYS is targeted at the elastic yielding of soil, and the Mohr-Coulomb criterion is applicable to slope issue.

Based on the previous research, there are three main criteria to judge whether the slope is instable by the strength reduction method: (1) whether the numerical calculation converges; [11] (2) whether the plastic zone of the slip belt is cut-through; [12-13] (3) Whether the soil displacement of the slip mass mutates and develops infinitely. [14] With the above basis, one can judge the stability of the slope.

4. Analysis of calculation

4.1 The optimal inclination angle of the anchor pile

The numerical simulation is carried out by changing the inclination angle *á* of the batter anchor pile without changing any other condition. The angle *á* is set as 5°, 10°, 15°, 20°, 25°, 30°, 35°, 40°, 45°, 50°, 55° and 60°. The plastic strains and displacements of some inclination angles at the ultimate failure state are calculated and displayed in the plastic strain nephogram and the displacement vectorgraph in Fig.3. It can be inferred from Fig.3(a) that stability coefficient of the model slope is 1.30 if it is not reinforced by the retaining structure. In this case, the weak slip belt is cut through by the plastic strain, most of the soil of the slope deforms greatly, and the maximum displacement occurs at the top of the upper slip mass. According to Figs.3(b) and 3(c), the plastic strain nephogram indicates that the combined retaining structure of batter anchor pile and slide-resistant pile at any inclination angle is able to cut off the plastic strain connection zone when the retained slope reaches the ultimate state. It means that overall slope damages will not occur even if the slip belt strength is further reduced. In addition, the displacement vectorgraph demonstrates that the displacement is obviously reduced after the slope has been reinforced by the combined retaining structure. The excellence of the retaining effect is also manifested by the fact that big deformation only occurs in front of the piles in the structure,



(a) Strain nephogram and displacement vectorgraph without retaining

(b) Plastic strain nephogram and displacement vectorgraph with an angle of 5°

(c) Plastic strain nephogram and displacement vectorgraph with an angle of 45°

Fig.3 The plastic strain nephograms and displacement vectorgraphs of the slope at the ultimate failure state of different angles

TABLE 2: THE STABILITY COEFFICIENTS AND MAXIMUM DISPLACEMENTS OF DIFFERENT INCLINATION ANGLES

Inclination angle (°)	5	10	15	20	25	30	35	40	45	50	55	60
Reduction coefficient	1.32	1.44	1.46	1.50	1.55	1.60	1.58	1.56	1.51	1.40	1.35	1.32
Displacement (cm)	24.4	27.0	28.3	28.9	29.9	29.5	29.3	28.0	27.8	26.5	25.3	24.2

TABLE 3: CALCULATION RESULTS OF DIFFERENT PILE DIAMETERS

Project / Pile diameter (mm)	Stability coefficient	Maximum displacement of slope (cm)		Maximum strain of the pile (cm)		Maximum horizontal stress of the pile (MPa)	Maximum vertical stress of the pile (MPa)	Maximum plastic strain of slip belt
200	1.52	Horizontal	18.9	Horizontal	11.9	124.0	36.9	0.238
		Vertical	23.5	Vertical	6.8	-101.0	-44.1	
400	1.60	Horizontal	19.2	Horizontal	11.4	115.0	35.2	0.244
		Vertical	23.8	Vertical	6.9	-95.3	-42.0	
700	1.63	Horizontal	18.7	Horizontal	10.2	102.0	32.3	0.239
		Vertical	23.2	Vertical	6.6	-88.1	-38.4	
900	1.64	Horizontal	18.4	Horizontal	9.7	94.2	30.0	0.241
		Vertical	22.9	Vertical	6.3	-85.5	-36.2	

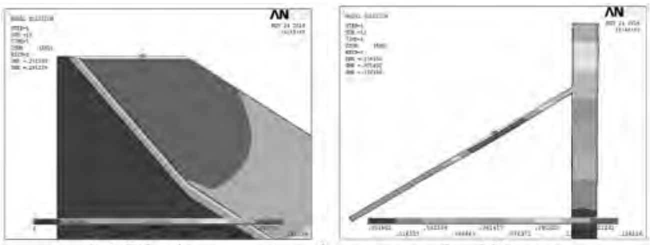
and little deformation takes place in the soil behind the piles.

In addition, the authors calculate the slope stability coefficients and maximum displacements at different inclination angles (Table 2). According to the results, the stability coefficient has increased after the slope is reinforced by the combined retaining structure, and the maximum displacement varies little (within 1~2 cm) with the ultimate failure state of different inclination angles. With the increase of the inclination angle, the slope stability coefficient changes in the following pattern: When the inclination angle of the batter anchor pile grows from 5° to 30°, the stability coefficient increases from 1.30 to 1.60; as the angle continues to expand, the stability coefficient begins to decrease. As for maximum displacement, it remains high at the ultimate failure state when the inclination angle of the batter anchor pile falls between 20° and 45°. This is mainly because of the large reduction coefficient at the time, which weakens the strength of the soil in the slip belt. In consideration of the economic effect and practical results, the inclination angle of the anchor pile should be put between 20° and 45° for the optimal reinforcement.

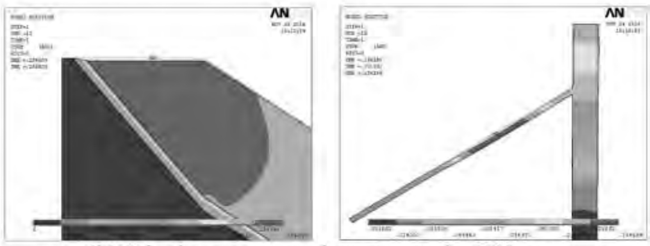
4.2 PILE DIAMETER

With other conditions remain unchanged, the authors establish a model by setting the optimal angle of the batter anchor pile á = 30° in reference to the results of the previous section, and uses the model to simulate different diameters of the anchor pile d_2. During simulation, d_2 is set as 100 mm, 200 mm, 300mm, 400 mm, 500 mm, 600 mm, 700 mm, 800 mm, and 900 mm. Some of the calculation results are shown in Table 3. It can be seen that the slope stability can always be improved significantly as long as the slope is reinforced with the combined retaining structure of batter anchor pile and slide-resistant pile, at whatever the pile diameter. Of course, the value of stability coefficient has something to do with the pile diameter. When the pile diameter is small (d_2<500 mm), the slope stability coefficient gradually increases with the pile diameter, and the increase is very obvious; when the pile diameter exceeds a certain size (d_2>500 mm), the stability coefficient has no obvious changes despite the increase of the pile diameter, indicating that the increase of diameter of the batter anchor pile could no longer improve the slope stability coefficient.

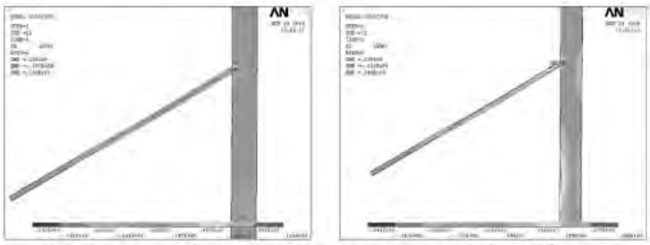
Moreover, the calculation results of different pile diameters of the batter anchor pile are presented in the following nephgrams. The slope displacement mainly occurs in the upper part of the slip mass before the pile, while the structural deformation concentrates in the free section of the anchor pile, where the pile is in contact with the sliding mass. As the pile diameter grows, both the displacement and deformation increase and then decrease. If the pile diameter is small, the displacement increment is very small (within 1 cm). Considering the big change of the stability coefficient in this case, the authors conclude that the increase of the pile diameter has an obvious effect on the deformation of the slope and the structure. Besides, the horizontal displacement at the top of the slide-resistant pile is decreasing, indicating that the increase in pile diameter can improve horizontal resistance of the batter anchor pile. If the pile diameter is large, the slope stability coefficient varies little and the displacement, too, has little changes. Thus, at this time, the increase in pile diameter can no longer restrict the displacement of the slope and the structure. It is worth mentioning that there are three stress concentration areas in the combined retaining structure, which are prone to damages. The areas are the connection between the batter anchor pile and slide-resistant pile, where the stress is the maximum, and the interfaces between the two piles and the slip belt. The stresses of the two piles are mainly tensile stress, and do not change much. In the plastic zone of the slip belt, the strain increases, then decreases, and in the end remains almost unchanged. The plastic strain increases first because the stability coefficient increases greatly when the pile diameter is small, so that the strength of the slip belt is



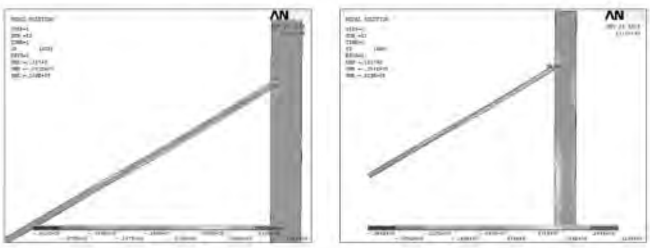
(a) Displacement nephogram at d_2=200 mm

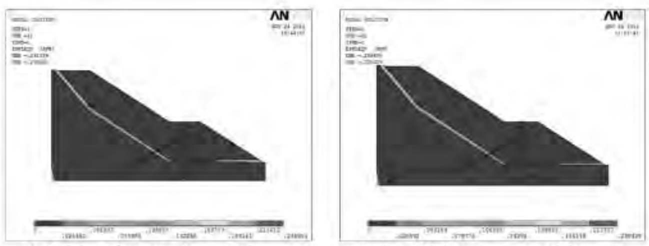


(b) Displacement nephogram at d_2=700 mm



(c) Stress nephogram of the structure at d_2=200 mm





(e) Plastic strain nephograms at d_2=200 mm or 400 mm

Fig.4 Nephograms of the calculation results of different anchor pile diameters

sharply reduced. After that, the strain decreases for the stability coefficient is almost constant when the pile diameter is large. In this case, although the increase in pile diameter can indeed reduce the plastic strain, the reduction is very limited.

To sum up, the diameter of the batter anchor pile should be determined in consideration of various factors, such as engineering geological conditions, retaining purpose, reinforcement requirements and economic benefits. The pile diameter should fall within a certain range because the function of the batter anchor pile would be constrained if the diameter is too small, and there would be unnecessary waste if the diameter is too big.

4.3 Anchorage depth

With other conditions remain unchanged, the author establishes a model by setting the optimal angle *á* = 30° and the pile diameter d_2=400 mm, in which the anchorage depth is put at 4 m, 5 m, 6 m, 7 m, 8 m, 9 m, 10 m, and 11 m. The results are shown in Table 4. It can be inferred that the stability coefficient increases with the anchorage depth when the anchoring depth of the batter anchor pile z = 4~8 m. The bigger the increase, the better the effect of the anchoring section. Due to the big increase in slope stability coefficient, the soil strength has been reduced significantly. Therefore, the displacement increases with the anchorage depth. When the anchorage depth z is greater than 8 m, the increase in anchorage depth has not obvious effect on the improvement of the anchorage depth because the stability coefficient has not changed much and the pile and soil have not displaced greatly.

The author then sorts out the relationship between the axial force distribution of the batter anchor pile along the anchoring section and the anchorage depth [15] (Fig.5). It can be seen that the axial force is largely distributed in the shape of parabola in the anchoring section of the anchor pile. The axial force is the greatest near the free section, and decreases with the increase of the anchoring depth. When the anchoring depth is small, the axial force distribution along the anchoring section differs greatly with the depth, indicating that the anchoring section is fully effective. When the anchoring depth is big, the axial force distribution in the anchoring section differs little with the depth. In this case, the anchoring effect will not be improved significantly if the anchorage depth is further increased. Taking all these factors into account, the author points out that batter anchor pile should be driven no less than 8 m into the stable rock formation within the theoretical broken angle, but the distance should not be excessively deep for the sake of economic benefits.

4.4 Pile spacing

With other conditions remain unchanged, the author analyzes the calculation results of different pile spacings by setting the optimal angle *á* = 30°, the pile diameter d_2 =

TABLE 4: CALCULATION RESULTS AT DIFFERENT ANCHORAGE DEPTHS

Project / Anchorage depth (m)	Stability coefficient	Maximum displacement of slope (cm)		Maximum strain of the slope (cm)		Maximum horizontal stress of the pile (MPa)	Maximum vertical stress of the pile (MPa)	Maximum plastic strain of slip belt
4	1.45	Horizontal	17.1	Horizontal	10.0	107.0	32.9	0.219
		Vertical	21.7	Vertical	6.3	-91.1	-40.3	
6	1.52	Horizontal	18.2	Horizontal	10.7	111.0	34.0	0.229
		Vertical	22.7	Vertical	6.6	-92.5	-41.0	
8	1.60	Horizontal	19.2	Horizontal	11.4	115.0	35.2	0.244
		Vertical	23.8	Vertical	6.9	-95.3	-42.0	
10	1.61	Horizontal	19.5	Horizontal	11.6	115.0	35.1	0.248
		Vertical	23.9	Vertical	6.8	-96.9	-43.0	

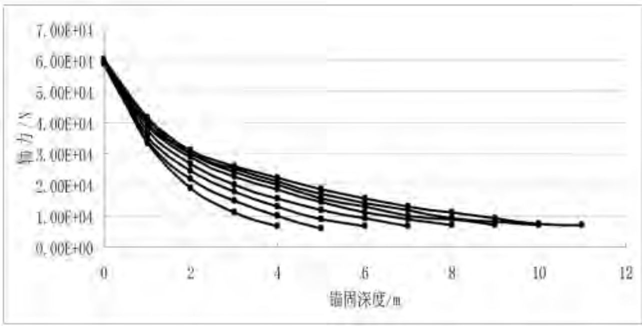


Fig.5 Relation curve of the axial force distribution along the anchoring section at different anchorage depths

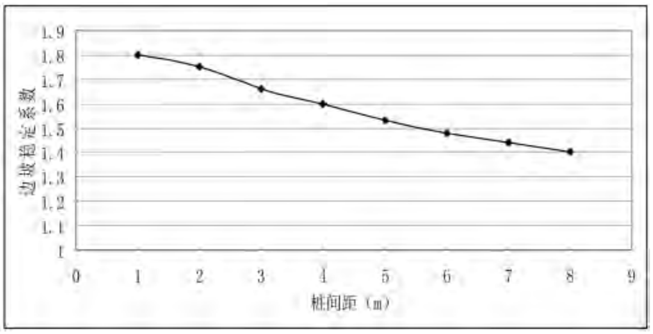


Fig.6 Relation curve of the slope stability coefficient at different pile spacings

400mm, and the anchorage depth z = 8m. The pile spacing is taken as 1m, 2m, 3m, 4m, 5m, 6m, 7m, and 8m. The results are shown in Figs.6~7. As shown in the figures, the stability coefficient of the slope decreases with the increase of the pile spacing, while the displacement of the pile and soil increases with pile spacing. In light of the gradual increase in horizontal displacement on the top of the slide-resistant pile, and the pullout effect at the bottom of the batter anchor pile, the author concludes that the combined retaining structure has more than enough slide resistance at small pile spacing, and the resistance increases with the decrease in pile spacing.

Figs.7(b) to 7(c) demonstrate that the stress distribution of the combined retaining structure is basically the same, which is consistent with the previous analysis. Nevertheless, the resistance of the structure is gradually stepped up as the pile spacing increases. This is testified by the simultaneous increase in horizontal, vertical and shear stresses, and the

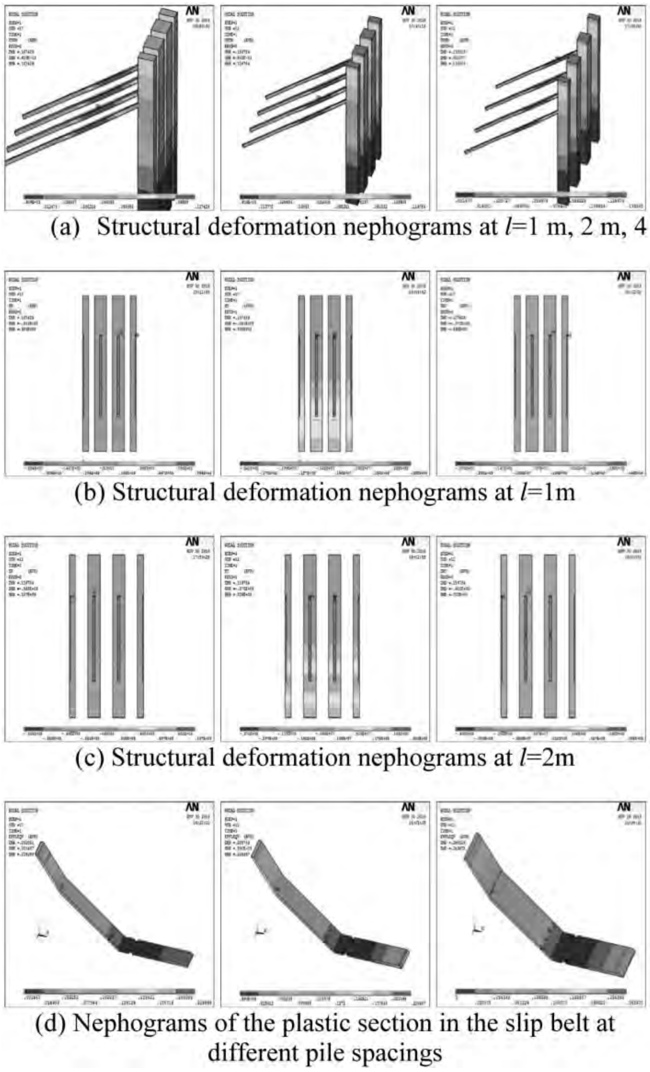


Fig.7 Nephograms of the calculation results at different pile spacings

expansion and development of the darker parts, i.e. areas with relatively stronger stress. As illustrated in Fig.7(d), the growth in pile spacing also promotes the development and increase of the plastic strain of the soil in the slip belt behind the pile. As a result, the pile spacing must be determined through comprehensive consideration of the degree of fragmentation of the rock and earth mass and the size of pile diameter. Proper pile spacing gives full play to the slide resistance effect of the slide-resistant pile and the anchoring effect of the batter anchor pile, and forcefully guarantees the economic efficiency of the design. As above, the pile spacing should be 2~3 times the pile diameter.

5. Conclusions

This paper establishes the model by ANSYS, and calculates the different characteristics of the combined retaining structure of batter anchor pile and slide-resistant pile. The proper parameters are obtained by looking at how the slope stability and load bearing properties of the structure changes with parameters like the inclination angle of the anchor pile, pile diameter, anchorage depth, and pile spacing. The main conclusions are as follows:

(1) After the slope is reinforced by the combined retaining structure, the slope stability coefficient has increased and then decreased when the inclination angle of the anchor pile changes from 0° to 60°. This indicates that the angle has an impact on the shearing force of the anchor pile on the rock mass and the anchorage depth into the stable rock stratum, and in turn affects the stability of the slope. Hence, the inclination angle of the anchor pile should fall between 20° and 45°.

(2) To reinforce the slope in an economic way, the pile diameter should fall within a certain range. If the diameter of the batter anchor pile is too small, the slope is not fully reinforced; if the pile diameter is too big, the stability improvement of high slopes is very limited, which resulting in unnecessary waste.

(3) In theory, the slope is more stable at a deeper anchorage depth. However, the study discovers that the anchoring effect is fully exerted when the anchorage depth reaches a certain extent. Any further increase in the anchorage depth will not lead to significant improvement of high slope stability coefficient. Thus, the pile should be driven no less than 8m into the moderately weathered rock formation which is stable within the theoretical broken angle, but the distance should not be excessively deep.

(4) Pile spacing has a great influence on both the batter anchor pile and the slide-resistant pile: if the pile distance is too small, the anchoring effect might be weakened by the multi-anchorage effect of the batter anchor piles, while a large horizontal resistance would be provided by the densely distributed slide-resistant piles; if the pile distance is too large, the batter anchor pile cannot retain the small particles in the rock and soil mass; more slope loads will be borne by the soil in the soil arch. Sometimes, it is simply impossible to form a soil arch. Hence, the pile spacing should be 2~3 times the pile diameter.

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