Research on discrete element simulation of anchor frame beam reinforcement in bedding shale slope

Xiao yong ZHANG, Xiao ting XIE

College of geology and environment, Xi'an University of Science and Technology, Xi'an, Shaanxi 710061, China

Email: 775451203@qq.com

Abstract. The anchor frame beam is a new type of composite support method, which is a kind of slope protection structure considering the interaction between the anchors and the slope. Based on the reinforcement project of a bedding shale slope in Chengzhang highway, the reinforced effect of anchor frame beam is studied by discrete element method. Firstly, the mesoscopic parameters of the rock mass are obtained by calibration while that of anchor frame beam are obtained by calculation. Then the slope model with the reinforcement of anchor frame beam is established by particle flow software PFC^{2D}. Afterwards, the statement of slope can be analyzed and the reinforcement effect of anchor frame beam can be predicted. Results show that: there is no instability in the slope after reinforcement, and the sliding of slope can be effectively prevented by anchor frame beam. The simulation results can provide reference for the design and construction of the project.

1. Introduction

The anchor frame beam is a new type of composite support method, which is a kind of slope protection structure considering the interaction between the anchors and the slope. Anchor is a "passive" support structure and the deformation of rock mass is delivered to anchors through the bonding material, which reduces reinforcement. The frame beam embedded in the slope is connected with the anchors which forms the whole structure of the anchor frame beam [1-3].

Discrete element method (DEM) is a kind of quantitative evaluation method. It is based on the explicit numerical algorithm to describe the movement and interaction of the granular media by defining various contact relationships among the particles, while allowing the particles to separate from each other and reconstruct new contacts in calculation process, so it has the superiority in the discontinuous medium simulation.

The particle flow method is one of the discrete element methods, which use circular particles to simulate geotechnical materials or other granular media. Related researches on the numerical simulation of the anchor frame beam have already been carried out by domestic and foreign scholars.

The excavation under soil nailing protection is established in reference [4]. Displacement fields and stress fields with and without soil nailing wall are analyzed respectively. The regulation in excavating process and the mechanism of soil nailing support are also studied. Evolution law of stress distribution and its influencing factors in anchoring section is studied in reference [5] by combining indoor experiment with particle flow simulation.

In conclusion, anchor frame beam has been simulated by discrete element method. The feasibility of the discrete element analysis is verified and the calculation method of the simulation parameters is put forward, while the application is super less in practical engineering. In this paper, the PFC^{2D}

particle flow method is used to study the stability of the slope before and after the slope reinforcement, and the reinforcement effect is forecasted, which can provide reference for the practical engineering.

2 Engineering Geology

Chengzhang highway excavation is located in Fengning County, Hebei Province. The slope is about 193.9m long and the excavation is about 33.1m deep. Slope is located in the low mountainous area with multi-peaked hills, steep slopes, crisscross gulleys. It belongs to cretaceous xiguayuan formation. It consists of fully weathered shale, strong weathered shale and mediate weathered shale [6].

Through the pre-geological survey, it's found that the slope is in an unstable state. It is recommended to reinforce the slope with anchor frame beam. The reinforcement scheme is as follows: 6 rows of anchors are arranged evenly on the surface of slope--- 3 rows of anchors in the first slope and 3 rows in the second slope. Horizontal and vertical spacing are 3m and anchorage angle is 20°. 32mm HRB335 type steel is adopted and every bundle of anchor consists of two anchors. The diameter of anchor is 150 mm, and anchorage section is 4m long. The length of anchor in each row are shown in Table 6. Section area is 300 mm × 400mm and the thickness of concrete protective layer is 50 mm. C30 concrete is adopted.

Table 1 The length of anchors in all rows

row	Free segment length /m	Anchored segment length /m	Total length /m
Row one	8.98	4	12.98
Row two	7.60	4	11.60
Row three	6.28	4	10.28
Row four	4.80	4	8.80
Row five	3.21	4	7.21
Row six	1.61	4	5.61

3 Determination of meso-parameters

3.1 Meso-parameters of all soil layers

The parameters in the PFC are meso-parameters, including particle contact modulus, bond strength and friction coefficient. These parameters do not correspond to the mechanical parameters obtained in laboratory tests. Therefore, the experimental parameters cannot be directly used in PFC simulation [7]. Uniaxial compression simulation test is used to determine the meso-parameters of the slope model. The linear stiffness model, the Coulomb friction model and the parallel bond model are adopted to simulate. The meso-parameters of the PFC model are shown in Table 2[8].

Table 2 Meso-parameters of PFC model

Particle parameters	Fully weathered shale	Strong weathered shale	Mediate weathered shale
Particle contact module/Pa	6.5e7	2e9	5e9
Stiffness ratio	1	1	1
Parallel bond module/Pa	6.5e7	2e9	5e9
S_bond/n-bond	1	1	1
Parallel tensile stress/Pa	5.5e4	4.2e6	12e6
Parallel cohesion/Pa	5.5e4	4.2e6	12e6
Parallel friction angle/°	15	18	20
friction	0.01	0.1	0.5
density/（kg/m^{-3}）	2300	2600	2700

3.2 Meso-parameters of anchor frame beam

PFC^{2D} program commonly use contact bond model and parallel bond model. In contact bond model, particals contact in points which can withstand tensile force and shear force, but cannot bear the bending moment; In parallel bond model, particles contact in a range of circles or rectangles which can withstand not only tensile force and shear force but also bear bending moment. This model is suitable for simulating the cohesive material and bending members [9-10]. Therefore, parallel bond model is adopted to simulate anchor frame beam in this paper.

Table 3 mechanical parameters of anchor frame beam

Mechanical parameters of anchors	Value	Mechanical parameters of frame beam	Value
Elastic module /Pa	4.5e10	Elastic module /Pa	2.5e10
Shear strength/Pa	1.8e10	Shear strength/Pa	1e10
Density/（kg/m^{-3}）	2600	Density/（kg/m^{-3}）	2600
Sectional area/m	0.071	Sectional area/m	0.12

The physical parameters of the anchor frame beam are shown in table 3. The parameters of anchor and geotechnical materials can be converted by equation (1):

$$\bar{k}_n = \frac{E}{\bar{L}},\quad \bar{k}_s = \frac{G}{\bar{L}},\quad k_n = k_s = \frac{2nAE}{L} \qquad (1)$$

In which:

E -- elastic modulus of the anchor；G -- shear modulus of the anchor; $\bar{L}$ -- the length of the parallel bond between the two particles;L-- the length of the anchor; A -- section area;n -- the number of parallel bond, $n = \lfloor L/2R \rfloor$;R -- radius of particle in anchor; $\bar{k}_n$ -- normal bond strength of parallel bond; $\bar{k}_s$ -- shear bond strength of parallel bond; k_n -- normal stiffness of particles; k_s -- shear stiffness of particles.

Meso-parameters in pile simulation are show in table 4.

Table 4 Meso-parameters of anchor frame beam

Parameters	Anchor	Frame beam
Particle contact module/Pa	3.2e9	3e9
Stiffness ratio	1	1
Parallel bond module/Pa	3e11	1.2e11
S_bond/n-bond	1	1
Parallel tensile stress/Pa	1e7	1e6
Parallel cohesion/Pa	1e7	1e6
Parallel friction angle/°	30	30
Friction	1	1
Density/（kg/m^{-3}）	2600	2600

4 The establishment of slope discrete element model

4.1 The establishment of slope model

The model build is generated by the deletion method. Firstly, generate DXF file in CAD software and then import it into the PFC. The ball distribution command is used to generate particle aggregates. After cycles, the model is in equilibrium state, and then remove the excess particles to generate the slope model. After particles in the model are grouped, we get the final discrete element model of the whole slope.

The number particles is 103478 and the radius of particles is 0.01m. In the picture, the blue particles represent fully weathered shale and the green particles demonstrate strong weathered shale, while the red part is mediate weathered shale.

4.2 The establishment of anchor frame beam model

The generating process of anchor frame beam is as follows: 1) use the ball command to generate a row of particles with a diameter of 0.15 m on the slope surface, which is simulating the frame beam; 2) remove the particles in the range of anchors, and then use the ball command to generate the anchor which consist of particles with a diameter of 0.15m; 3) Particles at the junction of the anchor and the frame beam are connected together by a clump command; 4) After cycles, the model is brought to equilibrium. Slope model is shown in Figure 1.

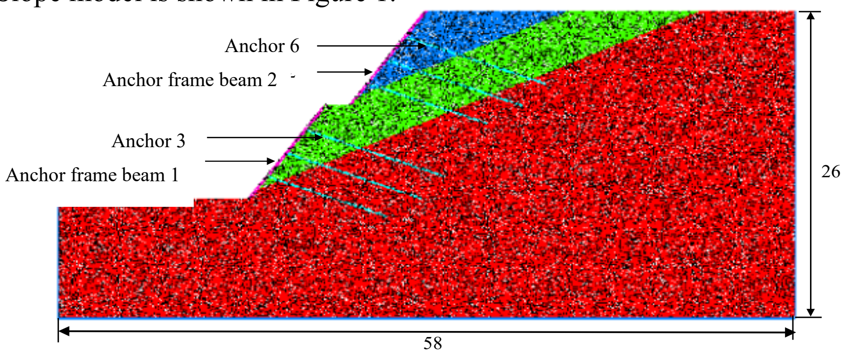
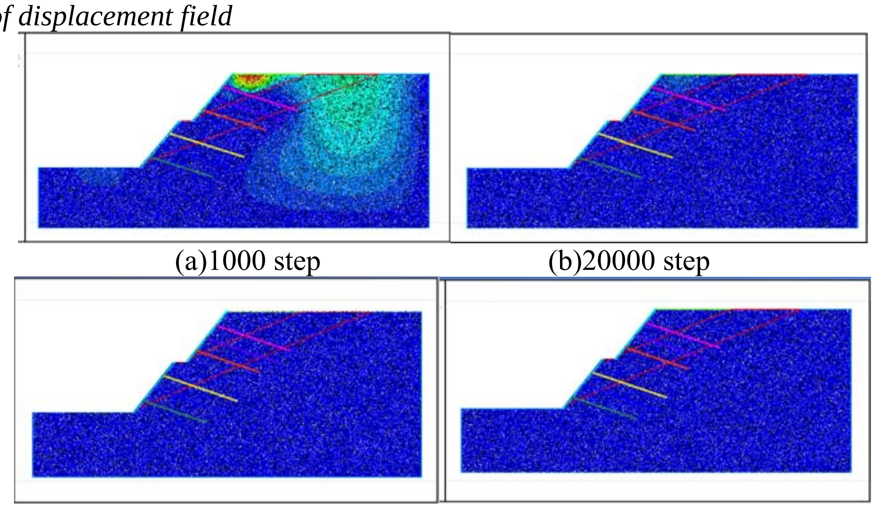


Figure 1 Discrete element model of slope (unit: m)

5 Analysis of sliding process

The gravity is applied to the slope. Use the delete command to remove the boundary walls, which is located on the surface of the slope and walls between soil layers. Then use the fix command to lock the particles on both sides and that at the bottom of the slope. The velocity and displacement of the particles in the model are cleared to facilitate the recording of the velocity and displacement of the slope. After applying gravity to the model, the model is destroyed and equilibrated after the cycle of 450000 steps.

5.1 Analysis of displacement field



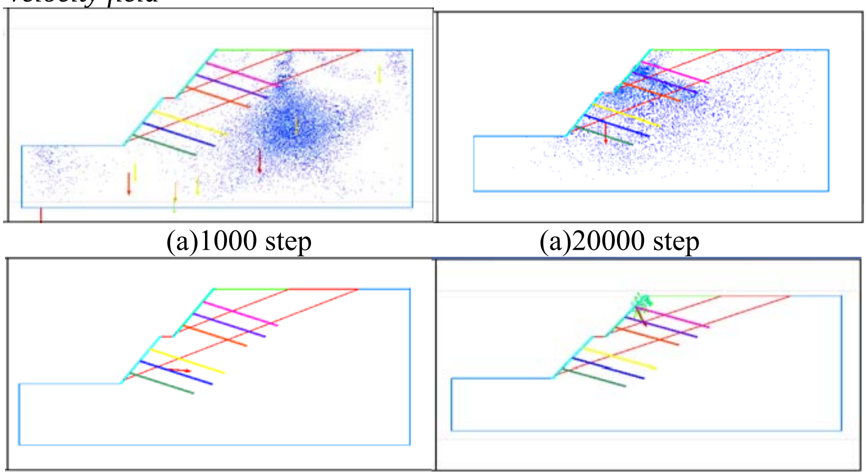
(a)1000 step (b)20000 step

(c)300000 step (d)450000 step

Figure. 2 The particle displacement of reinforced slope

The displacement field of the slope after reinforcement can be seen in Figure 2. After 1000 steps, sliding occur at the upper part above the first row of anchor in the fully weathered layer and the maximum value of displacement is 4.255e-4m; After 20000 steps, larger displacement only appear at a small scale, the maximum value of displacement is 4.5e-3m; After 450000 steps, the majority of particles in the slope did not shift and larger displacement only occur at a certain particles. The maximum value of displacement appears at the bottom of mediate weathered layer.

5.2 Analysis of velocity field



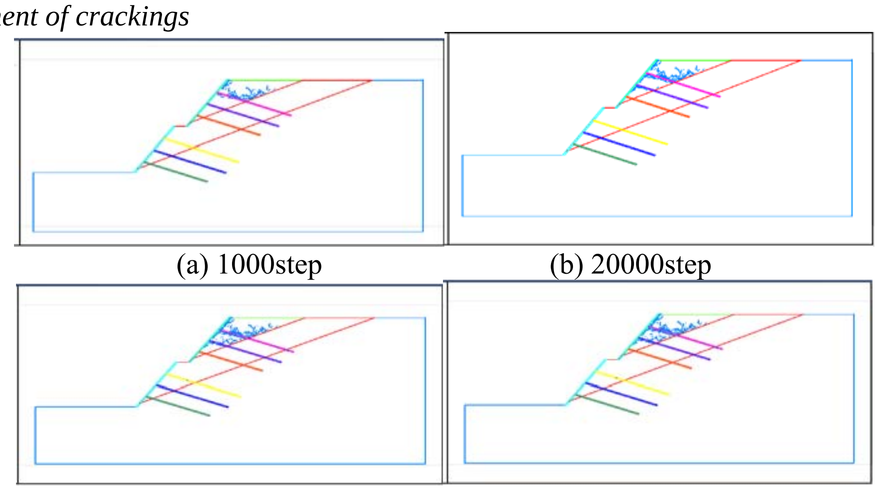
(a)1000 step (a)20000 step

(c)300000 step (d)450000 step

Figure. 3 The velocity vectors of reinforced slope

Figure3 shows velocity vectors in the slope after cycling different steps. After 1000 steps, the maximum value of speed is 4.96e-7m / step, which locates at the moderate weathered layer, and the direction of that is vertically downward; After 20000 steps, larger value of speed occur near the anchors. The maximum value of speed emerge in the vicinity of the anchor 2 and the value of that is 8.68e-9m / step, vertically downward; After 300000 steps, the maximum speed still locates in the vicinity of the anchor 2, while large speed did not appear at the rest of the slope . The maximum value of speed is 1.38e-5m / step; After 450000 steps, it can be found that the entire slope is in a stable state. Larger velocity vector appear at the shoulder of slope and the largest value of speed is 1.44e-11m / step.

5.3 Development of crackings



(a) 1000step (b) 20000step

(d) 300000step (d) 450000step

Figure.4 The cracking development of slope

The bond strength of the particles in the PFC software is determined by both the bond strength and friction coefficient between particles. If the actual tension or tangential force between the particles is greater than the corresponding bond strength, the bond between the particles will be destroyed. If the destruction of the bond strength occur, cracking develop at this location [11].

After 1000 steps, crackings mainly appear at the upper part above anchor 6 in the fully weathered layer and the number of crackings is 306; After 20000 steps, most crackings locate at the upper part above anchor 6 in the fully weathered layer while a small part of crackings locate near anchor 5. The total number of crackings is 453. After 300000 steps, the number of crackings between anchor 6 and anchor 5 is obviously increased and the number of crackings is 578. After 450000 steps, the number of crackings is 581 and will not increase any more, which indicates that slope cracking development has been in stabilization.

6 Conclusion

1) The advantage of using discrete element method to analyze slope stability is that there is no need to assume the sliding surface and constitutive relation, in which the whole failure process of slope can be directly observed.

2) The parameters obtained by uniaxial compression numerical tests can be used in the following study. The parallel bond model is used to simulate the anchor frame beam and the mesoscopic parameters of the anchor frame beam are also calculated.

3) After the reinforcement, the slope is in steady state, which indicates that the anchor frame beam effectively prevents the slope from being damaged. Therefore, the slope is suggested to be reinforced by anchor frame beam.

References

[1]ZHU H C. Measurements and Analysis on Bolt Stresses at a Slope [J]. Chinese Journal of Geotechnical Engineering, 2000, 22(4): 471-474.

[2]HAN A M, LI J G, XIAO J H, et al. Mechanical behaviors of frame beam supporting structure with prestressed anchors [J]. Rock and Soil Mechanics, 2010, 31(09): 2894-2900.

[3]ZHU Yan-peng, ZHENG Shan-yi, ZHANG Hong. Design of frame supporting structure with pre-stressed anchor bars on loess slopes [J]. Chinese Journal of Geotechnical Engineering, 2006, 28(Supp.): 1582－1585.

[4]ZHOU J, LI F, ZHANG J, et al. Study of PFC Numerical Simulation of Soil Nailing Wall Support Excavation[J]. Journal of Tongji University (Natural Science), 2011, 39(07):9 66-971.

[5]YI Y C, ZHAO TB, TAN Y L, et al. Research of stress distribution evolution law and influencing factors [J]. Journal of Mining & Safety Engineering, 2013, 30(05): 712-716.

[6]ZHANG X Y, YANG Z L, YUAN G A, et al. Stability analysis and reinforcement method of bedding shale slope [J]. Chinese Journal of Geotechnical Engineering, 2015, 37(S2): 176-180.

[7]ZHOU J, ZHANG L Q, DAI F C, et al. Numerical simulation of direct shear tests for rock and soil mixture in a landslide based on bonded-particl model [J]. Chinese Journal of Rock Mechanics and Engineering, 2013, 32(S1): 2650-2659.

[8]ZHANG X P, WU S C, ZHANG Z Z, et al. Numerical simulation and analysis of failure process of soil with weak intercalated layer [J]. Rock and Soil Mechanics, 2008, 29(5): 1200–1204.

[9]Itasca Consulting Group Incorporation. PFC^{2D} augmented Fish Tank[R]. Minnesota: Itasca Consulting Group Incorporation, 2004.

[10]SHI C, XU W Y. Numerical simulation techniques and practice of particle flow [M]. Beijing: China Construction Industry Press, 2015.