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RESEARCH ON THE REPRESENTATION OF GRANULAR VERTICAL SIZE GRADING AND NUMERICAL SIMULATION METHOD WITH THE TYPICAL WASTE ROCK SITE

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Original scientific paper
The vertical size grading of granular, as a typical characteristic with the high single-bench waste rock site, is an important factor affecting the slope stability of waste rock site. On the basis of field investigation of granular size distribution with the typical waste rock site, we used the Cellular Automaton method to develop the HHC-Granular model which could describe the phenomenon of apparent vertical size grading. Moreover, the slope model was constructed and size grading was considered with the aid of Flac^{3D} software based on the data collected from the typical waste rock site. The slope stability of various piling up patterns had been analyzed using the constructed slope model. The results indicated that at the top platform of waste rock site appeared the obvious tension cracks and slippage position of present slope was in the middle of waste rock site. The present slope was in the stage of temporarily steady. To adopt full overlay dump of multi-bench, the displacement vector of calculation images showed that the top of waste rock site was the subsidence and the horizontal distortion appeared at its bottom. The slope failure mode was that at the top platform of waste rock site appeared the cracks and its bottom showed the arc slippage. When the strength characteristics of granular were considered as the only factor in the slope stability analysis, the vertical size grading of high-bench waste rock site was helpful to slope stability.

Keywords: *HHC-Granular model; slope stability analysis; vertical size grading; waste rock site*

Istraživanje gradiranja veličine zrnatog materijala po vertikali i metoda numeričke simulacije tipičnog odlagališta jalovine

Izvorni znanstveni članak
Gradiranje zrnatog materijala po vertikali, kao tipično obilježje visokog odlagališta jalovine s jednim nasipom, važan je čimbenik koji utječe na stabilnost padine odlagališta jalovine. Na bazi terenskog istraživanja raspodjele veličine zrnatog materijala tipičnog odlagališta jalovine, primjenom Cellular Automaton metode razvili smo HHC-Granular model za opis pojave gradiranja po vertikali. Što više, konstruiran je model padine, a za gradiranje veličine upotrebljen je Flac^{3D} softver na temelju podataka prikupljenih na tipičnom odlagalištu jalovine. Stabilnost padine kod različitih načina odlaganja analizirala se primjenom konstruiranog modela padine. Rezultati su pokazali da su se na gornjoj platformi odlagališta pojavile pukotine zbog naprezanja, a klizište postojeće padine nastalo je u sredini odlagališta jalovine. Stanje postojeće padine bilo je privremeno stabilno. Za potpuno prekrivanje odlagališta s više nasipa, vektor premještanja računalnih slika pokazao je da je na vrhu odlagališta jalovine uleknuće, a na dnu se pojavila horizontalna distorzija. Do puknuća padine može doći ako se na gornjoj platformi odlagališta pojave napukline, a na dnu klizanje luka. Kad su se razmotrile karakteristike čvrstoće zrnatog materijala kao jedini faktor u analizi stabilnosti padine, gradiranje veličine zrnatog materijala po vertikali pomoglo je u stabilnosti odlagališta jalovine.

Ključne riječi: *odlagalište jalovine; gradiranje veličine po vertikali; HHC-Granular model; analiza stabilnosti padine*

1 Introduction

The area of waste rock site and refuse heaps had reached (1,4 ÷ 2,0)×10^4 km^2 in China, with an annual growth of 340 km^2. However, the national strength only supported reclamation rate of 6 %. Therefore, developing the high-bench dumping technology and establishing high-bench waste rock site is the essential means which could dramatically reduce the mining area [1]. However, the high-bench waste rock site, as the most common geologic body generated in the human engineering activities, bred a series of geological hazards and caused many geological problems, which still seriously threaten the human survival and the safety of engineering construction. The height of waste rock site was 120 m and it adopted the whole section height dump of single-bench. Fig. 1 displays the on-site survey maps and plane distributive maps of crack. Fig. 1 shows that there exists a large number of cracks in the top platform for the waste rock site. These cracks extend very long and the slope is also significantly bulgy. These cracks are relatively new and the size of width is small. However, some landslide or other hazardous incidents might occur at the waste rock site due to external forces. The hazardous incidents not only threaten the safety of persons and equipments in the dumping, but also might affect the safety of tailing dam which was close to the waste rock site. Therefore, it was absolutely necessary to analyse the slope stability.

The major distinction between high-bench waste rock site and general soil slope was that the high-bench waste rock site was the whole section height dump of single-bench and had apparent particle size grading. However, most of the engineers greatly simplified the important characteristic in the analysis of slope stability [2, 3, 4]. As we all know, the strength parameters of accumulational granular is a critical factor to perform slope stability analysis. Meanwhile, the granular composition is the main factor which influences the strength parameters. Therefore, it is unscientific and unreasonable to neglect the granular vertical size grading when the slope stability analysis is carried out. There are two main factors why the engineers did not consider the important feature of high-bench waste rock site. First, the data of granular distribution were difficult to obtain. Secondly, the reasonable values of granular strength parameters were difficult to determine because of the uniformity of granular distribution, and the condition constraint [5 ÷ 9].

Based on the study of earth-rock mixture, Shi-Hai Li [10] showed that earth-rock mixture has two characteristics which are the nonuniformity of granular shapes and sizes, and the random distribution of accumulational granular in the space. Therefore, it is difficult to directly obtain mechanical properties. However, it was much easier to acquire the mechanical properties of stone and soil respectively. The studies done by Japanese researchers also showed that the sample diameter did not influence the stress-strain curve obviously when the sample was homogeneous. Meanwhile, the internal friction angle of large size sample was smaller when the sample was inhomogeneous. Based on the above research result, the granular of waste rock sites was graded into different categories in order to reduce the particle size range and increase the uniformity of test samples.Then the relatively reasonable mechanical parameters were measured relying on the laboratory test. Meanwhile, the percentages of each granular media were entered when the slope stability was carried out. Thus,we did not need to set different mechanical parameters for each layer. This not only could save a lot of manpower, financial resources and time, but also improve the reliability of slope calculation.

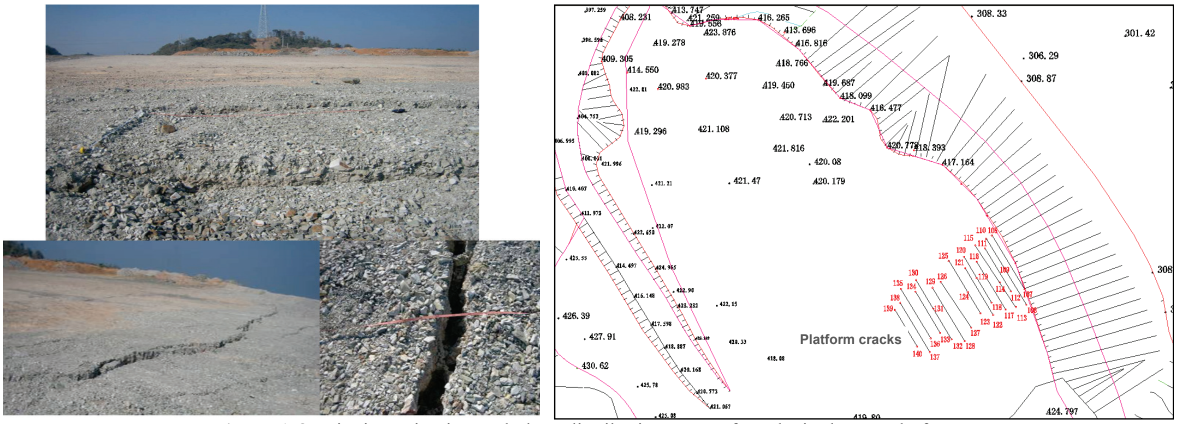

Figure 1 On-site investigation and plane distributive maps of cracks in the top platform

2 Engineering geology and site survey

The area of the waste rock site was about 2,5 km^2 and its elevations were 125 ÷ 410 m. The district of waste rock site had many v-shaped ravines. The width of the ravine was generally 20 ÷ 100 m. The survey results are shown in Fig. 2a. As Fig. 2a shows, the location of waste rock site is surrounded on three sides by mountains. Its material composition is the slightly weathered phyllite rock and the surface of accumulational granular is the loose accumulation. The slope of waste rock site has emerged slightly upheaval in the middle.

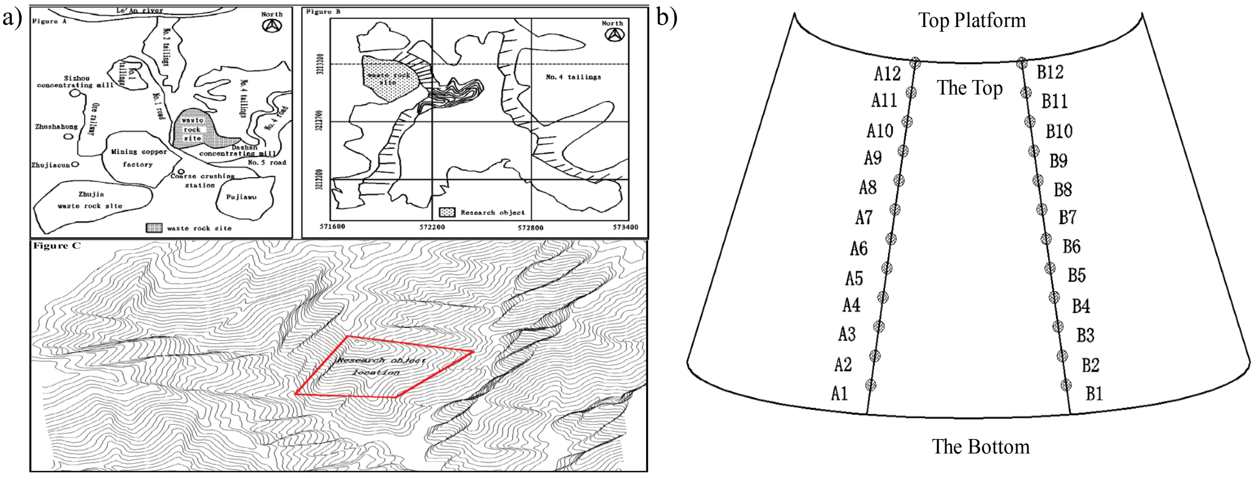

Figure 2 Geological situation and arrangement sketch of grain-size measuring points waste rock site: a) geological situation, b) grain-size measuring points

Based on the screening and direct measure methods, the article did the on-site investigation into the particle size distribution of granular materials with the waste rock site. The mesh size of on-site screening was 5 mm, 10 mm, 20 mm, 40 mm, 60 mm, 80 mm and 100 mm. For the large rocks which were inconvenient to screen, we used a ruler to directly measure the length of three mutually perpendicular directions of rock. The granular was classified into three categories according to the particle size: Powdery-Granular Granular (less than 10 mm), Small-Block Granular (10 ÷ 60 mm), Large-Block Granular (greater than 60 mm) [11].

The granular of waste rock site was generated from the stope explosion. The original blasting granular of greater stiffness was relatively little changed to compare with the original blasting granular [12]. Therefore, the article used the blasted granular to represent the no grading granular of waste rock site and chose three no grading granular materials to do the size survey at the top platform of waste rock site. The results are shown in Tab. 1. Meanwhile, in order to obtain the particle size with the change of waste rock site height, two representative survey lines were shown in Fig. 2b. The slope of waste rock site deployed a test point at 10 m intervals. The results showed that the particle size was changed with the height of waste rock site slope (see Fig. 1 of Tab. 2). The on-site size survey of slope showed that granular size distribution appeared significantly regular with the change of waste rock site height.

Table 1 Granular classification and blasting accumulated granular fragmentation results

Granular names	Powdery-granular granular	Small-block granular	Large-block granular
Size (mm)	$d < 10$	$10 \leq d \geq 60$	$d > 60$
Average contents of blasting granular (%)	24,3	48,0	27,7

3 HHC-Granular model and slope model

The Cellular Automata (CA) has discrete features on the time and space. The Cellular Automata (CA) is not determined by the physical equation or function, but is made up of rules constructed by a series of models.There is no fixed mathematical formula constructing the cellular automata. Meanwhile, each variable takes only the limited number of states. Ai-xiang wu [13] divided granular into three categories: Powder-Granular Granular, Small-Block Granular and Large-Block Granular). Therefore, the article generated randomly three different contents of material by the HHC-Granular model and it respectively showed the Powder-Granular Granular, Small-Block Granular and Large-Block Granular. The space grid number of HHC-Granular model and the units of each layer's accumulational granular was consistent. The model interface and generated randomly granular material is shown in Fig. 3.

The waste rock site adopted the whole section height dump of single-bench to dump and the height of bench was up to 120m. To be consistent with the actual slope, three-dimensional geological model was created in the CAD according to the original topographic map and current situation topographic map of waste rock site. Then the constructed model is inserted into ANSYS to set up slope mesh model. The on-site picture and model are shown in Fig. 4.

According to the on-site investigation of granular size distribution, combined with the development of the the HHC-Granular model was used to simulate the granular of waste rock site.The generated accumulation body diagram and slope model by HHC-Granular model are shown in Fig. 5.

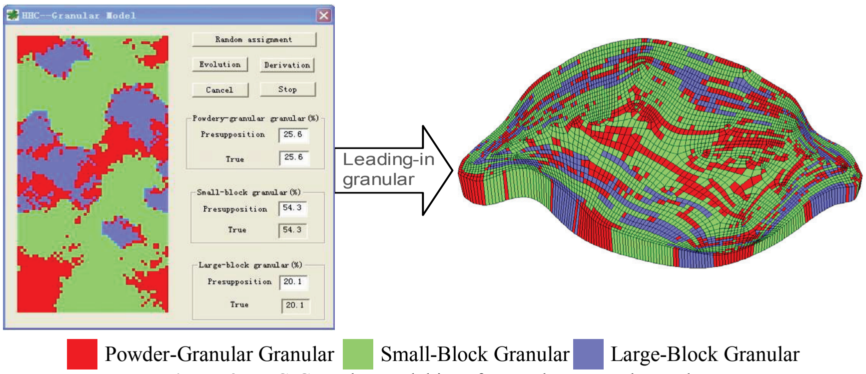

Figure 3 HHC-Granular model interface and generated sample

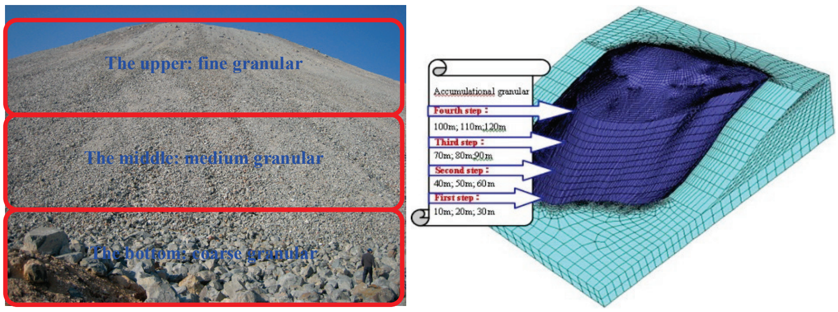

Figure 4 On-site picture and slope model of waste rock site

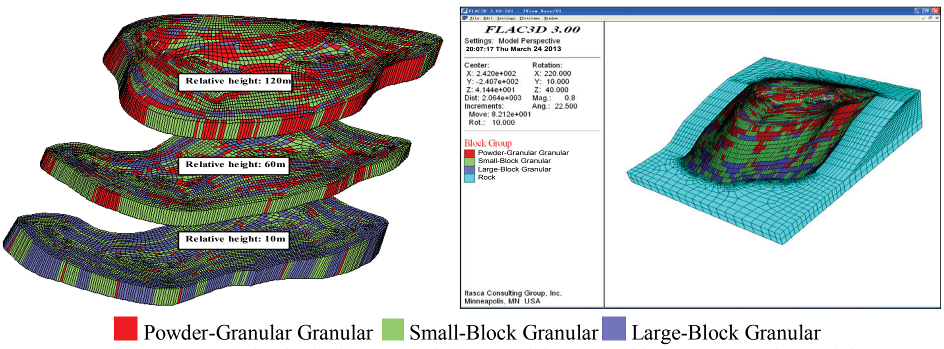

Figure 5 Accumulation body diagram and slope model generated by HHC-Granular model

Table 2 Granular particle size of waste rock site at different heights

Computational scheme	Granular	Size / mm	The relative height of the content of each block / %											
			The first bench			The second bench			The third bench			The fourth bench		
			10 m	20 m	30 m	40 m	50 m	60 m	70 m	80 m	90 m	100 m	110 m	120 m
Scheme 1	Powder-Granular	d<10	5,6	12,0	8,8	15,4	19,1	18,3	27,5	25,6	30,0	37,3	36,8	38,6
	Small-block	10≤d≤60	33,2	42,4	43,6	48,9	54,0	51,9	49,7	54,3	50,5	47,7	45,6	46,9
	Large-block	d>60	61,2	45,6	47,6	35,7	26,9	29,8	22,8	20,1	19,5	15,0	17,6	14,5
Scheme 2	Powder-Granular	d<10	24,3▲			16,0	20,0	21,0	23,0	26,0	29,0	30,0	32,0	34,0
	Small-block	10≤d≤60	48,0▲			50,0	49,0	49,0	50,0	48,0	49,0	49,0	48,0	48,0
	Large-block	d>60	27,7▲			34,0	31,0	30,0	27,0	26,0	22,0	21,0	20,0	18,0
Scheme 3	Powder-Granular	d<10	28,0	29,0	30,0	31,0	32,0	33,0	28,0	29,0	30,0	31,0	32,0	33,0
	Small-block	10≤d≤60	27,0	27,0	28,0	28,0	28,0	29,0	27,0	27,0	28,0	28,0	28,0	29,0
	Large-block	d>60	45,0	44,0	42,0	41,0	40,0	38,0	45,0	44,0	42,0	41,0	40,0	38,0
Scheme 4	Powder-Granular	d<10	16,0	20,0	21,0	23,0	26,0	29,0	30,0	32,0	34,0	24,3▲ 48,0▲ 27,7▲		
	Small-block	10≤d≤60	50,0	49,0	49,0	50,0	48,0	49,0	49,0	48,0	48,0			
	Large-block	d>60	34,0	31,0	30,0	27,0	26,0	22,0	21,0	20,0	18,0			
Scheme 5	Powder-Granular	d<10	24,3▲ 48,0▲ 27,7▲			28,0	29,0	30,0	31,0	32,0	33,0	24,3▲ 48,0▲ 27,7▲		
	Small-block	10≤d≤60				27,0	27,0	28,0	28,0	28,0	29,0			
	Large-block	d>60				45,0	44,0	42,0	41,0	40,0	38,0			
Scheme 6	Powder-Granular	d<10	24,3▲ 48,0▲ 27,7▲			24,3▲ 48,0▲ 27,7▲			28,0	29,0	30,0	31,0	32,0	33,0
	Small-block	10≤d≤60							27,0	27,0	28,0	28,0	28,0	29,0
	Large-block	d>60							45,0	44,0	42,0	41,0	40,0	38,0
Scheme 7	Powder-Granular	d<10	28,0	29,0	30,0	31,0	32,0	33,0	24,3▲ 48,0▲ 27,7▲			24,3▲ 48,0▲ 27,7▲		
	Small-block	10≤d≤60	27,0	27,0	28,0	28,0	28,0	29,0						
	Large-block	d>60	45,0	44,0	42,0	41,0	40,0	38,0						
Scheme 8	Powder-Granular	d<10	24,3▲ 48,0▲ 27,7▲			24,3▲ 48,0▲ 27,7▲			24,3▲ 48,0▲ 27,7▲			24,3▲ 48,0▲ 27,7▲		
	Small-block	10≤d≤60												
	Large-block	d>60												

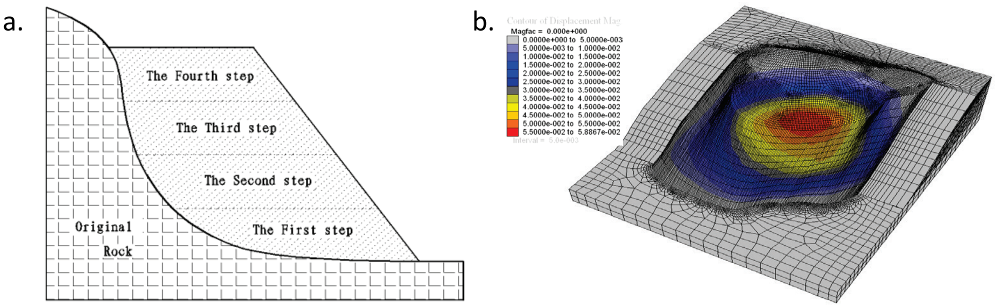

Figure 6 Piling up patterns and displacement cloud picture of waste rock site (a) Piling up patterns, (b) Displacement cloud picture)

4 Calculation schemes HHC-Granular model and slope model

Increasing the height of waste rock site was the most effective way to reduce the occupied fields of waste rock site and increase volume. In the same occupied fields, height and volume, the piling up patterns of waste rock site had the whole section height dump of single-bench and the full overlay dump of multi-bench, which is indicated in Fig. 6a.

From the on-site investigation, when the height of single-bench was less than 30 m, the particle size grading was not obvious. Therefore, to study the impact of piling up pattern on waste rock site stability, the article considered the single-bench height less than 30 m as the no grading granular media of waste rock site. Based on the above assumption, the accumulation body of waste rock site was divided into four benches.The first bench height was 0 ÷ 30 m, the second bench height was 30 ÷ 60 m, the third bench height was 60 ÷ 90 m, the fourth bench height was 90 ÷ 120 m. The key problem of engineering design was to ensure both the bench height and the slope stability. Therefore, to compare the whole section height dump of single-bench with the full overlay dump of multi-bench of different piling up pattern we have proposed 8 different dumping schemes. The distribution of particle size for each scheme is shown in Tab. 2. The scheme 1 is the whole section height dump of single-bench and scheme 2 to scheme 8 are the full overlay dump of multi-bench. The ▲ indicates the average contents of blasting granular in Tab. 2. The ▲ indicate that the percentage of granular particle size is not the on-site measured data, but the artificially set percentage according to the dumping schemes. The scheme1 studies the slope stability based on the on-site measured percentages of granular particle size.

5 Result and analysis

The calculating constitutive model adopted the Mohr-Coulomb model. The top of model was set to be free boundary, the bottom was set to be fixed boundary with constraints, and the four sides of the model were the roller bearing boundary. The gravity load was considered in the entire calculation process. The granular material parameters of Powder-Granular Granular, Small-Block Granular and Large-Block Granular are from the stability report of waste rock site [14] in the slope stability calculations. The specific material parameters are shown in Tab. 3.

Table 3 Material parameters of accumulation granular

Granular names	Density (kg/m^3)	Bulk modulus (GPa)	Shear modulus (GPa)	Cohesion (MPa)	Internal frictional angle (°)	Dilation angle (°)	Tensile strength (MPa)
Powder-Granular	1900	0,045	0,015	0,030	28,90	6,10	0,08
Small-block	2250	0,150	0,095	0,089	35,60	8,50	0,70
Large-block	2450	0,850	0,500	0,142	40,50	11,60	1,80
Rock	2800	2,500	2,600	0,286	45,00	16,80	2,30

Fig. 6b is the calculated displacement cloud picture based on the on-site measured granular particle size distribution. The figure shows that there is an obvious displacement concentration zone in the slope frontal edge. This zone has relatively high displacement value and obvious change of gradient. The displacement distribution is expressed in"enclosed shape" with the upper part of accumulational granular and maximum displacement range is located in the shoulder of top platform with the waste rock site.

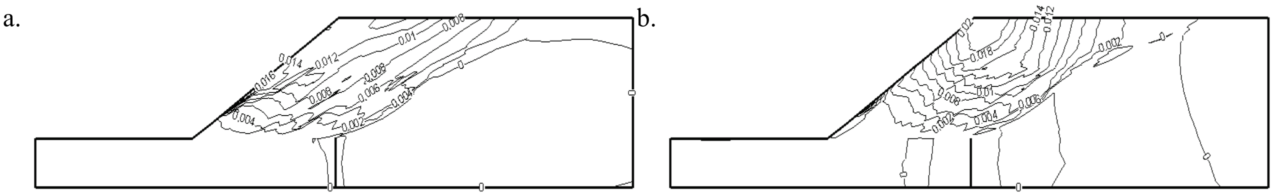

Figure 7 Displacement contours with high-bench waste rock site (a) *Y* direction, (b) *Z* direction (Unit: m)

Meanwhile, by means of the TECPLOT software, the calculated result of scheme 1 was converted into the displacement contours. Fig. 7 shows the *Y* and *Z* direction displacement contours. From the *Y* direction displacement contour as shown in Fig. 7a, it can be seen that the direction of displacement contour is the same as the slope direction in the upper part of waste rock site. And then the direction is nearly level in the middle part of the waste rock site. The Y displacement increases gradually from slope internal to slope outside and its maximum value appears in the slope surface of middle part of waste rock site. On the contrary, the displacement of bottom part and upper part of waste rock site is relatively small, and it shows that the middle part of waste rock site is the potential slide location. The displacement contour of *Z* direction in Fig. 7b shows that the displacement contour presents "semi-enclosed U-shape" in the slope. The displacement increases with the increment of height in the waste rock site. Meanwhile, the variation range of displacement is 0,000 ÷ 0,02 m. It shows that the center of subsidence is situated at the top platform shoulder of waste rock site, while the subsidence quantity is minimum in the bottom part of waste rock site. The crack appeared at the top platform area because the subsidence quantity was different in different position of waste rock site. So the slope failure pattern was that the cracks appeared at the top platform of waste rock site and then the cracks developed downwards from top platform to middle part and the slide-out position was in the middle part of waste rock site. The above analytical results are the same as the damage pattern of on-site investigation.

The calculated displacement vector clouds in the different schemes indicate that the displacement vector features of different piling up patterns were significantly different in different position of waste rock site. Overall, the analysis of the whole section height dump of single-bench showed that the direction of slope upper displacement vector remained the same as that of current slope. Meanwhile,the deformation trace was under the control of slide surface shape. The middle displacement vector was level and showed slide-out.The displacement vector of bottom part had the rising trend. The displacement vector was different when the piling up pattern adopted the full overlay dump of multi-bench to dump. At the top of waste rock site, it showed subsidence and transited to the horizontal direction at the bottom. At the same time, we could see from the cloud that the piling up pattern was either the whole section height dump of single-bench or the full overlay dump of multi-bench, the displacement reduced gradually with the decreasing of height. Meanwhile, from the above analysis, we could sketch out the slide-out position of slip surface: the slide-outposition of the whole section height dump of single-bench was in the middle part of waste rock site and that of the full overlay dump of multi-bench was in bottom part.

Tab. 4 shows the calculated safety factor of different dumping scheme. The calculated safety factor of scheme I is 1,258 and greater than 1,15, so the waste rock site is in temporary stable stage at present. However,when the waste rock site is influenced by external forces or other external factors, the slope might become unstable. Thus, appropriate engineering measures should be taken to reduce the risk. From the calculated safety factor in Tab. 5, its order is as follows: Scheme 1 > Scheme 2 > Scheme 3 > Scheme 4 > Scheme 6 > Scheme 5 > Scheme 7 > Scheme 8. From the calculation results, we know that the safety factors increase with the increment of Large-Block Granular in the bottom part and middlepart of waste rock site. Therefore, it shows that the whole section height dump of single-bench is superior to the full overlay dump of multi-bench when the influence of granular strength on slope stability of waste rock site is only taken into account.

Table 4 Calculation results of slope reliability

Computational scheme	Scheme 1	Scheme 2	Scheme 3	Scheme 4	Scheme 5	Scheme 6	Scheme 7	Scheme 8
Safety factor	1,258	1,212	1,184	1,161	1,136	1,157	1,104	1,092

6 Conclusion

The aim of constructing high-bench waste rock site was to develop resources and protect environment. However, because the physical and mechanical properties of granular materials were particular and complex, its landslide was significantly different with others. Therefore, to carry out slope stability research of high-bench waste rock site was of great significance.

(1) The article simulated different granular size distribution to use the developed HHC-Granular model. On the basis of the on-site survey of granular size distribution and geological data, the slope model was established to consider the particle size grading. The results showed that the granular samples, which were generated by the HHC-Granular model, could express the characteristics of particle size grading in the high-bench waste rock site.

(2) The results of slope stability analysis show that the waste rock site is in temporary stable stage at present. However, the slope might become unstable when the waste rock site is influenced by external forces or other external factors. It is needed to take proper engineering measures to lower the risks. Major task was to prevent possible landslide damage to the waste rock site in its upper part and middle part.

(3) The article compared the whole section height dump of a single-bench with the full overlay dump of a multi-bench. The results showed that the slip mass volume of the former was small, the slip destruction degree was lower, the safety factors were higher and the slope was steady state. On the contrary, when the waste rock site adopted the full overlay dump of multi-bench to dump, the slip destruction degree was bigger.

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