Study on Field Relative Density Test Method of Blasting Rockfill for High Rolled Rockfill Dams

Jianming Zhao\textsuperscript{1,a}, Renlong Huang\textsuperscript{1,b}, Yusheng Yang\textsuperscript{1,c}, Long Wang\textsuperscript{1,d}, Xiaosheng Liu\textsuperscript{1,e}, Zhengquan Yang\textsuperscript{1,f}

\textsuperscript{1}China Institute of Water Resources and Hydropower Research, Beijing, 100048, China

\textsuperscript{a}email: zhaojm@iwhr.com

\textsuperscript{b}email: 2975822649@qq.com, \textsuperscript{c}email: yangysh@iwhr.com,

\textsuperscript{d}email: 345335499@qq.com, \textsuperscript{e}email: liuxsh@iwhr.com, \textsuperscript{f}email: yangysh@iwhr.com

Abstract: At present, in the relevant design specifications for earth-rock fill dams in China, the filling standard of rockfill materials is expressed by porosity. Although the mechanical properties of coarse-grained soil are closely related to its porosity, the properties of coarse-grained soil with different gradations are not the same even if the porosity is the same. Porosity can’t express compactness, while relative density can represent compactness of coarse-grained soil. In order to control the deformation of dams reasonably, it is necessary to carry out the field relative density test of rockfill materials. In this paper, limestone rockfill is used to test. The results show that: (1) the bucket diameter of relative density tests has a certain influence on the maximum and minimum dry density of limestone rockfill. (2) In the range of test gradation lines, with the increase of the content of $P_5$, the maximum and minimum dry density all show the trend of increasing first and then decreasing. (3) When the content of $P_5$ is the same, the maximum and minimum dry density of limestone rockfill increase with the increase of the maximum particle size, and the particle size has a significant impact on the maximum and minimum dry density.

1. Introduction

Water conservancy and hydropower development is an important national strategy. More than 80% of Chinese hydropower resources are concentrated in the western region, where there are many mountains and valleys, and it is easy to build high dams and reservoirs with good regulation performance [1]. In recent years, with the rapid development of high earth-rock fill dam construction, great progress has been made in rockfill dam construction technology. A number of rockfill dams with a height of more than 200m, represented by Shuibuya [2] and Nuozhadu [3], have been built in China. The engineering scale of these dams is very large, which exceeds the mature design experience in the past. Furthermore, the geological conditions in the western region are complex, and they are located in the high seismic intensity area, with frequent seismic activities. This puts forward higher requirements for engineering deformation control and seismic safety, so it is very important to determine reasonable dam filling standard for engineering deformation control and seismic safety [4].

At present, in the relevant design specifications for earth-rock fill dams in China, the filling standard of sand gravel materials is expressed by relative density, and the filling standard of rockfill materials is expressed by porosity. It should be noted that the classical granular mechanics theory [5] holds that the deformation of rockfill materials as granular materials is mainly caused by void compression and relative
movement of particles, and its strength mainly depends on the sliding, crushing and rolling properties of particles. Using porosity to characterize the compactness of rockfill can eliminate the influence of mineral composition difference (specific gravity) to a certain extent, but can’t eliminate the influence of particle size difference. However, relative density can better reflect the influence of compactness of rockfill on the engineering mechanical properties (including compaction performance), and can make the comparison of engineering mechanical properties between rockfill bodies with different mineral composition and different particle gradation. By the confined compression test, Zhu Sheng et al. [6] found that for different grading rockfill materials, although the same porosity can be achieved by taking appropriate compaction measures, their mechanical properties are quite different, and it is difficult to control the deformation performance of dams with a single porosity index. Therefore, it is recommended to use dual control indexes of porosity and relative density.

In order to obtain the relative density of rockfill, it is required to conduct the relative density test. The relative density test is divided into indoor relative density test and field large-scale relative density test. Due to the limitation of equipment size in the laboratory, it is necessary to scale in the test, and the compaction method and compaction parameters are different from those in the construction site, so the test results can not reflect the true maximum and minimum dry density of the original graded rockfill materials [7-8]. Therefore, in order to eliminate the size effect and the influence of different compaction methods as far as possible and to determine the relative density index of rockfill reasonably, it is necessary to carry out field large-scale relative density tests of rockfill.

For sand gravel, there is a mature field large-scale relative density test method [9], and have been successfully applied in Xinjiang Dashixia [10], Yulongkashi and Altash [11], but there is no complete and mature field relative density test method for blasting rockfill. In this paper, the influence of density bucket diameter, maximum particle size and gradation parameters on the test results is investigated by carrying out field large-scale relative density tests of blasting rockfill, which provides parameters for field large-scale relative density tests of blasting rockfill.

2. Descriptions of test

2.1. Test principles

According to the test specification, the relative density of coarse-grained soil refers to the ratio of the difference between the void ratio of the loosest soil and that of the field soil and the difference between the void ratio of the loosest soil and that of the closest soil. The expression is:

\[
D_i = \frac{e_{\text{max}} - e}{e_{\text{max}} - e_{\text{min}}}
\]

where \(D_i\) is the relative density; \(e_{\text{max}}\) is the void ratio of the loosest soil, i.e., the maximum void ratio; \(e\) is the void ratio of the field soil; and \(e_{\text{min}}\) is the void ratio of the closest soil, i.e., the minimum void ratio.

At the same time, using the formula (2), the expression of relative density can be expressed by dry density as formula (3).

\[
e = \frac{\rho_s}{\rho_d} - 1
\]

\[
D_i = \frac{(\rho_d - \rho_{\text{min}}) \rho_{\text{max}}}{(\rho_{\text{max}} - \rho_{\text{min}}) \rho_d}
\]

where \(D_i\) is the relative density; \(\rho_{\text{max}}\) is the maximum dry density; \(\rho_d\) is the dry density of the field soil; \(\rho_{\text{min}}\) is the minimum dry density; \(\rho_s\) is the density of soil particles.

According to the definition of relative density above, the maximum and minimum dry density of coarse grained soil must be determined in order to obtain the relative density.

2.2. Test scheme

In this paper, the limestone blasting rockfill is used to carry out the test. The test gradation of the influence of different bucket diameters adopts the test design gradation average line, as shown in table
1. The research results of sand gravel show that when the ratio of the diameter of the test bucket to the maximum particle size of the gravel ($D/d_{\text{max}}$) reaches 3, the effect of bucket diameter on test results can be ignored. The maximum particle size of the design gradation is 600mm, and the width of the vibration roller used in the field is 2.2m. Therefore, when studying the influence of bucket diameter on the relative density test results of rockfill materials, the range of $D/d_{\text{max}}$ is determined as 2 ~ 4, as shown in table 2.

Table 1. Design gradation of different bucket diameters tests

| particle size $d$ (mm) | 600 | 400 | 300 | 200 | 100 | 60 | 40 | 20 | 10 | 5 |
|------------------------|-----|-----|-----|-----|-----|----|----|----|----|----|
| test design gradation averaging line (%) | 100 | 85.5 | 76.4 | 64.8 | 48.5 | 38.5 | 31.4 | 22.1 | 15.2 | 10 |

Table 2. $D/d_{\text{max}}$ of different bucket diameters tests ($d_{\text{max}}$=600 mm)

| $D/d_{\text{max}}$ | 2 | 2.5 | 3 | 3.5 | 4 |
|-------------------|---|----|---|----|---|
| bucket diameter $D$ (m) | 1.2 | 1.5 | 1.8 | 2.1 | 2.4 |

Under the condition that the density bucket diameter is determined, the relative density test of limestone rockfill is carried out, according to the gradation curve shown in table 3, to study the influence of gradation (different contents of $P_5$) on the maximum and minimum dry density of rockfill.

Table 3. Gradation table of relative density tests of limestone rockfill

| particle size (mm) | 600 | 400 | 200 | 100 | 60 | 40 | 20 | 10 | 5 |
|-------------------|-----|-----|-----|-----|----|----|----|----|----|
| upper envelope (%) | 100 | 100 | 91.5 | 81.2 | 64.5 | 53.2 | 44.7 | 33 | 25.1 | 19 |
| upper average (%) | 100 | 92.75 | 83.95 | 73 | 56.5 | 45.85 | 38.05 | 27.55 | 20.15 | 14.5 |
| average (%) | 100 | 85.5 | 76.4 | 64.8 | 48.5 | 38.5 | 31.4 | 22.1 | 15.2 | 10 |
| lower average (%) | 100 | 76 | 66.7 | 55.5 | 40.25 | 31.25 | 25.05 | 17.05 | 11.35 | 7.5 |
| lower envelope (%) | 100 | 66.5 | 57 | 46.2 | 32 | 24 | 18.7 | 12 | 7.5 | 5 |

Based on the above determination of density bucket diameter, five groups of test gradation are designed to study the influence of the maximum particle size of rockfill on the maximum and minimum dry density. The five groups of test gradation have the same content of $P_5$, but the maximum particle size is 60mm ~ 600mm, as shown in table 4.

Table 4. Test design gradation table of limestone rockfill with the same content of $P_5$

| particle size $d$ (mm) | 600 | 400 | 200 | 100 | 60 | 40 | 20 | 10 | 5 |
|------------------------|-----|-----|-----|-----|----|----|----|----|----|
| gradation 1 (%) | | | | | 100 | 77.6 | 48.2 | 26.4 | 10 |
| gradation 2 (%) | | | | 100 | 76.6 | 60 | 38.3 | 22.2 | 10 |
| gradation 3 (%) | | | 100 | 73.2 | 56.8 | 45.1 | 29.9 | 18.5 | 10 |
| gradation 4 (%) | | | 100 | 75.3 | 55.9 | 44 | 35.5 | 24.4 | 16.2 | 10 |
| gradation 5 (%) | | | | 100 | 81.6 | 57.7 | 40.8 | 31.6 | 25.8 | 18.3 | 12.9 | 10 |

2.3. Main test equipment

Density bucket: steel bucket with bottom and no cover, with diameters of 1.2m, 1.5m, 1.8m, 2.1m and 2.4m, 800mm in height and 14mm in wall thickness.

26t vibration roller. The specific parameters are shown in table 5.

Table 5. Parameter table of the vibratory roller

| model | mass (t) | amplitude (strong / weak) (mm) | frequency of vibration (Hz) | vibration force (kN) | driving speed required (km/h) |
|-------|----------|--------------------------------|-----------------------------|----------------------|------------------------------|
| GLG6626S | 26 | 1.95/0.9 | 28/32 | 430/290 | 2~3 |

2.4. Test process

The minimum dry density tests were conducted by artificial loose filling method. The main process was as follows: selected rockfill from the material yard; transported the rockfill to the test site; screened the rockfill with sieves; weighed the mass of each particle group according to the test gradation; mixed
evenly in four parts; filled the rockfill in the density barrel gently; after filling to the top of the barrel, used a flat tool to level out the top of the density bucket; calculated the minimum dry density according to the total mass of filled soils and the volume of density bucket.

The maximum dry density tests were conducted by the vibration rolling method. The main process was as follows: on the basis of the above minimum dry density test, filled the remaining soils about 20cm higher than the top of the bucket; use the selected vibration roller to compact at the speed of 2~3 km/h; after 26 times of vibration compaction, conducted the micro motion advance and retreat vibration compaction within the range of each density barrel for 15min; after the completion of compaction, removed the surplus soils above the top of the bucket, leveled, excavated and weighed.

The part process of field relative density tests is shown in figure 1.

![Part pictures of field relative density tests](image)

Figure 1. Part pictures of field relative density tests. (a) Screening rockfill. (b) Minimum dry density test after leveling. (c) Vibration compaction. (d) Maximum dry density test excavation.

3. Results and analysis

3.1. The effect of bucket diameters on relative density test results of rockfill

Table 6 shows the test results of different bucket diameters, and figure 2 shows the variation of dry density of limestone rockfill with bucket diameters. It can be obtained from table 6 and figure 2 that the bucket diameter has a certain effect on the maximum and minimum dry density of limestone rockfill. When the bucket diameter is 1.2m ~ 1.8m, i.e. $D/d_{\text{max}}$ is 2 ~ 3, the maximum and minimum dry density of limestone rockfill increase with the increase of bucket diameters. When the bucket diameter is more than 1.8 m, i.e. $D/d_{\text{max}}$ is more than 3, the influence of bucket diameters on the maximum and minimum dry density is little. This is consistent with the test results of gravel materials, and also consistent with the understanding that the influence of equipment size on the test results can be ignored when the ratio of the size of indoor test equipment to the maximum particle size is more than 3.

Therefore, based on the maximum particle size of limestone rockfill in this test is 600mm, the density bucket of 1.8 m diameter is selected for the subsequent tests.
Table 6. Test results of different bucket diameters

| $D/d_{\max}$ | 2   | 2.5 | 3   | 3.5 | 4   |
|---------------|-----|-----|-----|-----|-----|
| bucket diameter $D$ (m) | 1.2 | 1.5 | 1.8 | 2.1 | 2.4 |
| minimum dry density (g/cm$^3$) | 1.820 | 1.839 | 1.858 | 1.851 | 1.857 |
| maximum dry density (g/cm$^3$) | 2.324 | 2.335 | 2.361 | 2.357 | 2.360 |

Figure 2. The variation of dry density of limestone rockfill with bucket diameters

3.2. The influence of gradation on relative density test results of rockfill

Table 7 and figure 2 show the test results of gradation envelope of limestone rockfill materials. It can be seen from the table and figure that within the range of test grading envelope, with the increase of the content of $P_5$, the maximum and minimum dry density of limestone rockfill increase at first and then decrease. The dry density is the largest near the average gradation, and the corresponding maximum and minimum dry density are 2.337g/cm$^3$ and 1.818g/cm$^3$ respectively. It can be seen that the gradation has a great influence on the relative density test results of rockfill.

Table 7. Test results of gradation envelope of limestone rockfill

| gradation | upper envelope | upper average | average | lower average | lower envelope |
|------------|----------------|---------------|---------|---------------|----------------|
| content of $P_5$ (%) | 81.0 | 85.5 | 90.0 | 92.5 | 95.0 |
| minimum dry density (g/cm$^3$) | 1.751 | 1.781 | 1.818 | 1.803 | 1.755 |
| maximum dry density (g/cm$^3$) | 2.256 | 2.313 | 2.337 | 2.309 | 2.262 |
Figure 3. Relationship between the dry density and content of $P_5$ of limestone rockfill

According to the above test results, the maximum and minimum dry density first increase and then decrease with the content of $P_5$, which may be due to the existence of an optimal content of $P_5$ ($P_5$-optimal). When $P_5 < P_5$-optimal, the content of coarse-grained material is not enough, and the coarse-grained material does not play a role of skeleton completely. The fine material can not only completely fill voids, but also have surplus. The mass of fine material with the same volume is smaller than that of coarse-grained material, which leads to the increase of dry density with the increase of the content of $P_5$. When $P_5 = P_5$-optimal, the coarse-grained materials play a role of skeleton completely, and the fine materials can fill voids completely and reach the maximum dry density. When $P_5 > P_5$-optimal, the content of fine material is not enough to completely fill voids formed by coarse-grained material, resulting in the decrease of dry density with the increase of the content of $P_5$.

3.3. The influence of maximum particle size of rockfill on relative density test results with the same content of $P_5$

With the same content of $P_5$, the influence of the maximum particle size of limestone rockfill on the relative density test results is shown in table 8 and figure 3. It can be seen from the table and figure that when the content of $P_5$ is the same, the maximum dry density of limestone rockfill increases with the increase of maximum particle size. When the maximum particle size is less than 600 mm, the minimum dry density also increases with the increase of the maximum particle size, and decreases when the maximum particle size is 600 mm. It can be seen that the particle size has a significant effect on the maximum and minimum dry density of the test, showing an obvious size effect. It also shows that the indoor relative density test can’t be directly used to calculate the relative density of rockfill because of the scale.

Table 8. Test results of different maximum particle sizes with the same content of $P_5$

| maximum particle size (mm) | 60 | 100 | 200 | 400 | 600 |
|---------------------------|----|-----|-----|-----|-----|
| minimum dry density (g/cm³) | 1.606 | 1.687 | 1.772 | 1.866 | 1.812 |
| maximum dry density (g/cm³) | 1.961 | 2.056 | 2.160 | 2.249 | 2.325 |
Figure 4. Relationship between the dry density and maximum particle size of limestone rockfill with the same content of $P_5$

4. Conclusion

The analysis performed in this study leads to the following conclusions:

1) The bucket diameter of relative density tests has a certain influence on the maximum and minimum dry density of limestone rockfill. When the bucket diameter is 1.2 m ~ 1.8 m, i.e. $D/d_{\text{max}}$ is 2 ~ 3, the maximum and minimum dry density of limestone rockfill increase with the increase of bucket diameter. When the bucket diameter reaches 1.8 m, i.e. $D/d_{\text{max}}$ reaches 3, the influence of bucket diameter on the maximum and minimum dry density can be ignored. Therefore, it is suggested that $D/d_{\text{max}}$ should reach 3 when the relative density test of blasting rockfill is done in the field.

2) Field relative density tests were carried out with density buckets of 1.8 m diameter on the gradation envelope of limestone rockfill. The test results show that, within the range of test gradation envelope, with the increase of the content of $P_5$, the maximum and minimum dry density increase at first and then decrease, and there is an optimal content of $P_5$.

3) When the content of $P_5$ is the same, the test results show that the maximum and minimum dry density increase with the increase of the maximum particle size (60 mm ~ 400 mm). The particle size has a significant effect on the maximum and minimum dry density of the test, showing an obvious size effect.

Acknowledgments

This study was funded by National Key R&D Program of China (2017YFC0404905).

References

[1] Zhou JP, Yang ZY, Chen GF. (2006) Present situation and challenges of high dam construction in China. Journal of Hydraulic Engineering, 12: 1433-1438.
[2] Yang ZY, Zhou JP, Wang FQ, et al. (2017) 30 years development of concrete face rockfill dams in China. Hydropower and pumped Storage, 3(01): 1-5+12.
[3] He FJ, Li YL, Shi PF. (2014) Summary of safety monitoring technology and operation experience of high core wall rockfill dams in China. In: Technical Progress in High Dam Construction and Operation Management —— Annual Conference of China Dam Association 2014. Guiyang. pp: 400-405.
[4] Zhao JM, Wen YF, Liu XS, et al. (2010) Analysis of ultimate seismic capacity of high earth-rock fill dams on deep overburden. Rock and Soil Mechanics, 31(S1): 41-47.
[5] Li GX. (2016) Advanced soil mechanics. Second edition. Tsinghua University Press, Beijing.
[6] Zhu S, Zhong CX, Zheng XL, et al. (2018) Study on filling standard and gradation optimization of rockfill. Chinese Journal of Geotechnical Engineering, 40(01): 108-115.
[7] Feng GQ, Yang YH. (1992) Study on the indoor test methods of maximum index density of rockfill.
Chinese Journal of Geotechnical Engineering, 05: 37-45.

[8] Zhu S, Zhong CX, Wang J, et al. (2019) Experimental study on filling standard of high core wall rockfill dams. Chinese Journal of Geotechnical Engineering, 41(03): 561-566.

[9] Tian KL, Zhang HL, Zhang BP, et al. (2002) Determination method of filling standard for oversize cohesionless coarse grained soil. Journal of Northwest A&F University (Natural Science Edition), 30(6): 193-197.

[10] Dong CS, Yang ZQ, Wang L, et al. (2018) Field large-scale relative density tests of gravel soil of Dashixia high concrete faced rockfill dam. Journal of Jilin University (Earth Science Edition), 48(05): 1603-1608.

[11] Wang L, Li YP, Wang ZJ, Gao F, Liu QW. (2018) Experiment on relative density of sand-gravel material for construction of concrete faced rockfill dam for Altash Water Control Project and its engineering application. Water Resources and Hydropower Engineering, 49(S1): 21-26.