A method of determining the optimal fine-grained content soil of rockfill materials in view of different maximal grain sizes

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Abstract: To solve the problem that the optimal fine-grained content of rockfill materials is regardless of the maximal grain sizes, fractal theory was imported and fractal dimension was used. The process of determining the optimal fine-grained content with different values of \(d_{\text{max}}\) was described in detail. A theoretical formula considering of the influence of the maximal grain sizes was established. Then an example was made and verification was carried out further. The result indicates that the theoretical formula can be used to predict the optimal fine-grained content in view of different maximal grain sizes.

1. Introduction

Rockfill materials are widely used in the rockfill dams. The grain sizes distribute from 0.075mm to 1200mm, which leads to large spatial variability. At present, the gradation of rockfill materials is based on Talbot curve which is continuous. Experimental investigation shows that the gradation has large density. Rockfill materials need certain shear strength, which confines to the maximal the fine-grained content. Here, fine grain size is less than 5mm and \(p_{5}\) means the fine-grained content in the following sections. The standard[1] requires that \(p_{5}\) should be less than 20% in field and the standard[2] requires that \(p_{5}\) should be less than 30% in laboratory tests. In field, the maximal grain size is between 600mm and 1200mm. However, in laboratory, the maximal grain size is not more than 60mm. Obviously, \(p_{5}\) is related to the maximal grain size. So far, the relation has not been clear and relevant studies are few.

Fractal theory has its unique advantages in describing macroscopic randomness and variability, which has been widely used in geotechnical field[3-8]. As a result, fractal theory was applied to the relation between \(p_{5}\) and the maximal grain size in the paper.

2. Application of fractal theory to gradation of rockfill materials

S W Tyler and S W Wheatcraft [9] verified that fractal theory is satisfied in three-dimensional space when the following equation exists:

\[
V(d > d_{i}) = C_{m} \left[ 1 - \left( \frac{d_{i}}{d_{m}} \right)^{3-D} \right]
\]  

(1)
C_m and \lambda_m are parameters reflecting particle shape and size. D is fractal dimension. V is volume. \(d_i\) is characteristic particle size.

Equation (1) can be translated equation (2) expressed in terms of mass \(M\):

\[
M \left( d > d_i \right) = \rho_p V = \rho_p C_m \left[ 1 - \left( \frac{d_i}{\lambda_m} \right)^{3-D} \right]
\]

\(\rho_p\) is specific gravity.

Substitute boundary conditions which are \(d_i=0\), \(M=M_T\) and \(d_i=d_{\text{max}}\), \(M=0\) to equation (2):

\[
\frac{M \left( d > d_i \right)}{M_T} = 1 - \left( \frac{d_i}{d_{\text{max}}} \right)^{3-D}
\]

\(M_T=\rho_p C_m\) which represents the total mass and \(d_{\text{max}}=\lambda_m\) which represents the maximal diameter of gradation.

Equation (3) is equivalent to equation (4):

\[
p_i = 100 \left( \frac{d_i}{d_{\text{max}}} \right)^{3-D}
\]

\(p_i\) is mass percentage when \(d \leq d_i\).

The fine-grained content in the paper is \(p_5\) when \(d=5\text{mm}\):

\[
p_5 = 100 \left( \frac{5}{d_{\text{max}}} \right)^{3-D}
\]

3. Implementation process

The method of determining the optimal fine-grained content soil of rockfill materials in view of different maximal grain sizes can be summarized in Figure 1.

Make relative density tests.

Establish relationships between the maximal porosity or the minimal porosity and fractal dimension \(D\).

Determine the optimal fractal dimension \(D^*\).

Establish the theoretical formula of \(p_5^*\).

The value of \(p_5^*\) can be obtained by determining the value of \(d_{\text{max}}\).

Fig. 1 The implementation process

(1) Male relative density tests.

Design a series of gradations with different values of \(D\) and the same values of \(d_{\text{max}}\). Then, relative density tests with each gradation were made. The maximal porosity test uses Loose-in Method and the minimal porosity test uses Surface Vibrator Method.

(2) Establish relationships between the maximal porosity or the minimal porosity and fractal dimension \(D\).

From step (1), each gradation can obtain a maximal porosity(\(n_{\text{max}}\)) and a minimal porosity(\(n_{\text{min}}\). Then the relationship between the maximal porosity and \(D\) and the relationship between the minimal porosity and \(D\) can be determined.
(3) Determine the optimal fractal dimension $D^*$.  
The optimal fractal dimension $D^*$ is defined as the minimal value of $n_{\text{max}}$ or $n_{\text{min}}$ shown in Figure 2. From step (2), $D^*$ can be easily determined according to the curves.

(4) Establish the theoretical formula of $p_5^*$

The theoretical formula of $p_5^*$ is shown in equation (6):

$$p_5^* = 100 \left( \frac{5}{d_{\text{max}}} \right)^{3-D^*}$$  \hspace{1cm} (6)

(5) The value of $p_5^*$ can be obtained by determining the value of $d_{\text{max}}$.  
From equation (6), the value of $p_5^*$ can be obtained only by determining the value of $d_{\text{max}}$ as needed.

4. Example and verification

4.1 Example

The materials used are from one rockfill dam which is 300m height. The gradations are calculated by equation (4). The value of $d_{\text{max}}$ is 60mm and the values of $D$ are 2.30, 2.40, 2.50, 2.55, 2.60 and 2.70. there are 6 gradations in all. The typical relative density tests are shown in Figure 3. The relationships between the maximal porosity or the minimal proosity and $D$ are shown in Figure 4. From Figure 4, we can see that $D^*=2.55$. As a result, $p_5^*$ can be calculated by equation (7):

$$p_5^* = 100 \left( \frac{5}{d_{\text{max}}} \right)^{0.45}$$  \hspace{1cm} (7)

Fig. 3 The relative density test  
(a) the specimen of the maximal porosity (b) the specimen of the minimal porosity
Fig. 4 The relationships between porosity $n$ and $D$ ($d_{max}=60\text{mm}$)

According to equation (7), $p_5^*$ can be calculated when $d_{max}=40\text{mm}$:

$$p_5^* = 100 \left( \frac{5}{40} \right)^{0.45}$$

(8)

Finally, $p_5^*=39.2\%$ when $d_{max}=40\text{mm}$.

4.2 Verification

To verify the veracity of equation (8), another relative density test was made. The gradations are calculated by equation (4). The value of $d_{max}$ is 40mm and the values of $D$ are 2.30, 2.40, 2.50, 2.55, 2.60 and 2.70. The results are shown in Figure 5. $p_5^*$ can be directly determined which is 39.2% with $D=2.55$ gradation. Obviously, the theoretical formula in the paper is correct and can be used to predict $p_5^*$ with different values of $d_{max}$.

5. Conclusions

A theoretical formula was established using fractal theory and a method of determining the optimal fine-grained content soil of rockfill materials in view of different maximal grain sizes was suggested. The verification test indicates that the theoretical formula can be used to predict the optimal fine-grained content in view of different maximal grain sizes.

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