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**Defined Method of Naturally Graded Coarse-grained Materials’ Maximum Dry Density Based on Vibration Rolling Tests**

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**Abstract**

The energy method to obtain maximum dry density of rockfill is proposed by using on-site paving vibration rolling test data. Based on the principle of common vibration, the compaction energy of coarse-grained materials caused by vibration roller is calculated in order to build up the relationship of compaction energy and measured density. The method is applied in Shuibaya project which found that the relationship is closed to hyperbolic function, and then the relative density of coarse-grained materials is obtained which provides the basis for the relative density of coarse aggregate as the dam design and quality control indicator.

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**Keywords:** energy method; coarse-grained materials; compaction energy; dry density; relative density

1. **Introduction**

A single porosity or density cannot be used to measure the quality of compaction of coarse-grained dam materials, for it could bring blindness to evaluation of quality and safety of the project [1]. The specifications about earth-rockfill dams all specify the relative density parameter as compactness indicator [3~5] that should be used as dam design and quality control indicator [2]. However, the maximum density refers to the density of scaling grading materials. So scaling effect obviously exists. In addition the method and energy of compaction in laboratory is different from on-site vibrating...
compaction.
So the energy method to obtain maximum dry density of rockfill is proposed using on-site vibration rolling test data. According to the compaction theory, the maximum dry density of natural graduation is obtained which provides a rational basis for using relative density as design and quality control indicator.

2. Determination of Maximum Dry Density of Coarse-grained Materials

2.1. Compaction Mechanism of Vibrating Roller

2.1.1. Compaction Energy per Unit Area

Vibrating compaction produces quick and continuous impact at the surface of fillings that causes pressure waves to improve the compactness of coarse-grained materials. Fig. 1(a) illustrates that the whole coarse-grained dam materials is acted as viscoelastic-plasticity block fixed on the base surface.

![Fig. 1. (a)Compaction; (b)Work schedule](image)

The vertical displacement of coarse-grained materials on surface is equal to:

\[ x = \sum_{i=1}^{n} A_i \sin (\tilde{\omega} t - \alpha_i) \]  

(1)

Where \( A_i \) and \( \alpha_i \) represent amplitude and phase difference of each frequency respectively; \( \tilde{\omega} \) is excitation frequency; \( t \) is time.

Owing to high-order terms can be ignored, the vertical displacement can be written as below:

\[ x = A \sin (\tilde{\omega} t - \alpha) \]  

(2)

Only when the direction of force composed by gravity and vibratory force points down, the materials can be compacted that is shown in Fig. 1(b). Vibratory force and gravity of drum produce the effective energy in an oscillation cycle is equal to:

\[ E_0 = \int_0^T (W + F \sin \omega t) A \omega \cos (\tilde{\omega} t - \alpha) dt = 2WA + FA(\cos \alpha + \alpha \sin \alpha) \]  

(3)

Where \( W \) is net weight of the vibrating drum; \( A \) represents the amplitude of vibratory roller which can be obtained according to the parameters of rollers; \( \tilde{\omega} \) is natural frequency of materials ; \( \alpha \) is the phase difference due to the effect of damping.

Hertwig(1933) put forward principle of common vibration for compactness that the frequency of vibration lies in the range of natural frequency. Therefore optimal compaction can be achieved on this occasion. The natural frequency of coarse-grained materials almost range from 25Hz to 35Hz[7], while the excitation frequency of vibrating rollers is about 25–35Hz. When \( \tilde{\omega} \) is approximately equal to \( \omega \), Eq.(3) change to \( \alpha = \pi/2 \) and \( E_0 = 2A(W + \pi F/4) \) respectively. In one passing operation, the compaction energy per unit area results from vibratory roller that equals to:
\[ E = E_0 \cdot \frac{t}{T} \cdot \frac{1}{BL} = E_0 \cdot \frac{L}{v} \cdot \frac{1}{BL} = 2A \left( W + \frac{1}{4} \pi F \right) \frac{f}{Bv} \]  

(4)

Where \( E \) is compaction energy per unit area. Its unit is: \( N \cdot \text{cm/cm}^2 \); \( W \) and \( F \) refer to the weight of drum and vibratory force both of which unit is: \( N \); \( f \) is the frequency of vibratory roller both of which unit is: \( \text{Hz} \); \( A \) and \( B \) refer to the amplitude and width of the drum respectively both of which unit is: \( \text{cm} \); \( v \) is the velocity of the roller. Its unit is: \( \text{cm/s} \).

2.1.2. Average Energy of Layer

Whether the thickness of layer is 60cm, 80cm or 100cm, compaction degree is not uniform that the density near the surface is higher. The phenomenon indicates attenuation of pressure waves caused by vibratory rollers along the thickness of layer, which has been found in the density test of Shuibuyan[8].

Due to measured density represents average density for the thickness of layer, average compaction energy of the coarse aggregate filling need be calculated, which is According to reference[9],

2.2. Application

The Shuibuya concrete-faced rockfill dam is the highest of its kind in the world. The main rockfill district of dam is built by Maokou limestone (\( \rho_1^l \)). Large-scale compaction tests have been carried out using vibratory rollers of YZT16 and YZT18. The maximum density can be obtained following the steps below.

According to Eq.(4), compaction energy per unit area of land surface, which received one roller pass, is obtained. In addition, average energy of different thickness that can be calculated are listed in Table 3.

Table 3. On-site paving vibration rolling test data

<table>
<thead>
<tr>
<th>Type</th>
<th>Thickness (cm)</th>
<th>Roller passes</th>
<th>Average Density (g/cm³)</th>
<th>Average Energy (N \cdot \text{cm/cm}^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>60</td>
<td>4</td>
<td>2.143</td>
<td>527.79</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6</td>
<td>2.232</td>
<td>799.75</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8</td>
<td>2.247</td>
<td>1078.61</td>
</tr>
<tr>
<td>YZT16</td>
<td>80</td>
<td>4</td>
<td>2.127</td>
<td>436.70</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6</td>
<td>2.213</td>
<td>662.56</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8</td>
<td>2.225</td>
<td>887.46</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>4</td>
<td>2.104</td>
<td>362.70</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6</td>
<td>2.183</td>
<td>548.66</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8</td>
<td>2.198</td>
<td>738.42</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>10</td>
<td>2.220</td>
<td>930.95</td>
</tr>
<tr>
<td>YZT18</td>
<td>80</td>
<td>4</td>
<td>2.216</td>
<td>588.48</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6</td>
<td>2.262</td>
<td>893.87</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8</td>
<td>2.309</td>
<td>1203.77</td>
</tr>
</tbody>
</table>

Figure 3 presents the relation of average energy and tested density of different thickness of layer that is closed to hyperbolic function. The maximum density can be obtain with data-fit method:

\[ \rho_d = \frac{\bar{E}'}{(a + b \bar{E}') + \rho_0} \]  

(5)

Where \( \rho_d \) is measured dry density; \( \bar{E}' \) is average compaction energy of layer of different passes; \( a, b \) and \( \rho_0 \) are fitting parameters.
Fig.3. Relation of average energy and density \( \rho_d \) (Maokou limestone \( \rho_{dm1} \))

No matter the types of vibratory rollers, thickness of layer and rolling speed, the normalization of calculated maximum dry density can be observed. As energy approaches infinity, the density is closed to asymptotic value of hyperbola which can be regard as the evolution of maximum dry density. When the energy is 0, the parameter \( \rho_0 \) can be regard as the minimum dry density, which needs to be compared with the measured result in the project. Therefore the maximum dry density can be obtained in Table 4.

Table 4. Extreme value of dry density for natural gradation of coarse-grained materials

<table>
<thead>
<tr>
<th>Lithology</th>
<th>Specific Gravity</th>
<th>Maximum Density (g/cm(^3))</th>
<th>Minimum Density (g/cm(^3))</th>
<th>Porosity</th>
<th>Porosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maokou Limestone</td>
<td>2.72</td>
<td>2.43</td>
<td>1.77</td>
<td>0.119</td>
<td>0.536</td>
</tr>
</tbody>
</table>

According to reference 8, the designed porosity of main rockfill district is 0.196, while the measured porosity is 0.191. According to the calculated porosity in Table 4, the designed relative density of main rockfill is 0.69, while the real result is 0.73.

3. Conclusion

According to the test of on-site paving vibratory compaction, the relation of compaction energy caused by vibration roller and the measured density of coarse-grained materials is closed to hyperbolic function, then the maximum density can be calculated conveniently. Therefore the rational basis is provided for using relative density as indicator of design and quality control.

References