Prediction of Shear Strength Parameters for Prototype Riverbed Rockfill Material Using Index Properties

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ABSTRACT

Rockfill materials are being used widely in the construction of rockfill dam to trap river water because of their inherent flexibility, capacity to absorb large seismic energy and adoptability to various foundation conditions. Rockfill material is obtained from Noa Dehing dam site, Arunachal Pradesh. The maximum particle size of the material used in the dam is 600 mm. For testing, the size is scaled down to smaller sizes of 4.75, 10, 19, 25, 50 and 80 mm maximum particle size ($d_{\text{max}}$) using parallel gradation technique. Drained triaxial tests are carried out with a specimen size of 381 mm diameter and 813 mm height with varying confining pressure ($\sigma_3$) from 0.2 to 0.8 MPa. All the $d_{\text{max}}$ are tested for 87% and 75% relative density (RD). The index properties of the rockfill materials viz. unconfined compressive strength (UCS) and uncompacted void content (UVC) are determined. Stress-strain-volume change behaviour of the modelled rockfill material is studied and presented. The shear strength parameter, angle of internal friction ($\phi$) is determined for all the $d_{\text{max}}$ of modelled rockfill materials tested with 87% and 75% RD. Strength law has been developed to determine the failure stresses using index properties of rockfill materials viz. UCS, UVC and RD and then $\phi$ values are predicted for all the modelled rockfill materials satisfactorily. The $\phi$ value of the prototype rockfill material is predicted using the proposed strength law. The predicted $\phi$-value of prototype rockfill material is compared with the $\phi$-value predicted by commonly used extrapolation technique (power law which requires laboratory triaxial test results) based on $d_{\text{max}}$ and found that $\phi$ value match closely. Therefore, it is believed that the proposed method is more realistic, economical, can be used where large size triaxial testing facilities are not available and quick to determine $\phi$ value using index properties.

1. INTRODUCTION

Rockfill materials are widely being used all over the world in the construction of rockfill dams for harnessing the water resources. The behaviour of the rockfill materials is of considerable importance for the analysis and design of these rockfill dams.

Rockfill materials consist of maximum particle size ($d_{\text{max}}$) up to 1200 mm. Rockfill material with such a large particle size is not feasible to test in the laboratory. Some kind of modelling technique is often used to reduce the size of particles so that the specimens prepared with smaller size particles can be tested. Among all modeling techniques, the parallel gradation technique (Lowe 1964) is most commonly used. The behaviour of the riverbed rockfill material has been reported by number of researchers. Marsal (1967), Marachi et al. (1969), Gupta (2000), Abbas (2003), Abbas et al. (2003), CSMRS (2010) and Honkanadavar (2010) have performed laboratory tests on riverbed rockfill materials collected from different river valley projects from India and abroad. They concluded that stress-strain behaviour is non-linear, inelastic and stress level dependent. The volume change at failure increases with increase in confining pressure ($\sigma_3$) and $d_{\text{max}}$ for the riverbed rockfill materials. They also concluded that the shear strength parameter, angle of internal friction, $\phi$ increases with increase in $d_{\text{max}}$ for all the riverbed rockfill materials.

The material parameters of modelled rockfill materials obtained from the tests are generally used to get the parameters for the large prototype rockfill materials by extrapolation. Venkatachalam (1993) and Varadarajan et al. (2003) proposed power law to determine the parameter of prototype rockfill materials. The limitation of this technique is the dependence of the strength
parameter, $\phi$ only on $d_{\text{max}}$. Abbas (2003) and Varadarajan et al. (2006) proposed a strength law to determine the behaviour of prototype rockfill materials based on index properties of rockfill materials viz. unconfined compressive strength (UCS) and uncompact void content (UVC) only.

This paper deals with the testing of the rockfill materials obtained from Noa Dehing dam site, Arunachal Pradesh. Strength law has been proposed to express strength parameter of the rockfill materials in terms of UCS, UVC and relative density (RD). UCS represents the strength of the rock from which rockfill materials are derived and it is independent of $d_{\text{max}}$. UVC includes the effect of gradation, shape, size and surface texture of the rockfill materials and it is dependent of $d_{\text{max}}$. RD represents the relative compactness of the rockfill materials.

2. EXPERIMENTAL INVESTIGATIONS AND DISCUSSION

Material Used
To carry out this research work, rockfill material from Noa Dehing dam site, Arunachal Pradesh has been considered. The rock type is Dolomite, fine grained textured inequigranular rock and blue to dark gray in colour. The $d_{\text{max}}$ proposed in the construction of the Noa Dehing dam is 600 mm. The material has been modelled to six $d_{\text{max}}$ (4.75, 10, 19, 25, 50 and 80 mm) using parallel gradation technique as shown in Fig. 1 to test in the large size triaxial specimen of size 381 mm diameter and 813 mm height.

Experimental Programme

Determination of Index Properties
It is known that the shear strength of granular materials is dependent on RD, $\sigma_3$, individual particle strength, $d_{\text{max}}$, shape, surface texture and mineralogy.

The individual rockfill particle strength can be represented by UCS of the rock from which rockfill material is derived. Three cylindrical NX (54 mm diameter) size rock core specimens were tested using IS: 1943-1979 and average value of UCS is reported.

Shape, size, surface texture and gradation of the material are represented by a basic characteristic known as UVC for coarse material (ASTM C1252-98, Alhrich 1996). The fabricated apparatus to determine UVC of rockfill material is shown in Fig. 2.

The UVC apparatus is designed to test the modelled rockfill materials of $d_{\text{max}}$ = 4.75, 10 and 19 mm. To determine the UVC for $d_{\text{max}}$ of 25, 50, 80 and prototype (600 mm) rockfill material, following procedure has been adopted.

Three modelled rockfill materials of $d_{\text{max}}$ = 4.75, 10 and 19 mm were obtained using parallel gradation technique and they were tested to determine the UVC. The $d_{\text{max}}$ vs UVC has been plotted on semi-log graph and then the UVC for 25, 50, 80 and 600 mm $d_{\text{max}}$ is determined using a best fit linear extrapolation as

$$\text{UVC} = -0.04 \ln (d_{\text{max}}) + 0.548 \quad (1)$$

The determined index properties are given in Table 1.

Table 1: Properties of Riverbed Rockfill Materials

<table>
<thead>
<tr>
<th>Properties</th>
<th>RD (%)</th>
<th>$d_{\text{max}}$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>UVC</td>
<td>4.75</td>
<td>0.48</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>0.45</td>
</tr>
<tr>
<td></td>
<td>19</td>
<td>0.43</td>
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<tr>
<td></td>
<td>25</td>
<td>0.42</td>
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<td></td>
<td>50</td>
<td>0.39</td>
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<td></td>
<td>80</td>
<td>0.37</td>
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<tr>
<td>UCS (MPa)</td>
<td></td>
<td>85.32</td>
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<tr>
<td>$\phi$ (Degree)</td>
<td>75</td>
<td>36.31</td>
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<tr>
<td></td>
<td>38.62</td>
<td>39.87</td>
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<td></td>
<td>39.36</td>
<td>40.84</td>
</tr>
<tr>
<td></td>
<td>41.51</td>
<td>42.47</td>
</tr>
<tr>
<td></td>
<td>42.81</td>
<td>43.86</td>
</tr>
</tbody>
</table>

Drained Triaxial Test
Consolidated drained triaxial tests have been conducted on the modelled rockfill materials with confining pressure varying from 0.2 to 0.8 MPa for 87% and 75% RD at Central Soil and Materials Research Station (CSMRS), New Delhi.

The stress-strain-volume change behaviour of modelled rockfill material for 87% RD has been presented in Fig. 3. From the stress-strain plots, it is observed that the behaviour is non-linear, inelastic and stress level dependent. The deviatoric stress and axial strain at failure increases with increase in $d_{\text{max}}$ and $\sigma_3$. For the same $d_{\text{max}}$ and $\sigma_3$, the deviatoric stress at failure increases with increase in RD (results not reported). The volume change
behavior shows compression during the initial part of shearing and dilation with further shearing which decreases with increase in \( \max_d \) and \( \sigma_3 \). The volumetric strain at failure increases with \( \max_d \) and \( \sigma_3 \). For the same \( \max_d \) and \( \sigma_3 \), the volumetric strain at failure decreases with increase in RD (results not reported).

Mean stress \( v/s \) deviatoric stress was plotted and shear strength parameter, \( \phi \) is determined for all the \( \max_d \) tested with 87% and 75% RD. The experimental \( \phi \)-values are given in Table 1.

3. PREDICTION OF SHEAR STRENGTH PARAMETER USING INDEX PROPERTIES

The following strength law has been proposed in this research work for the rockfill material in the dimensionless form as

\[
\frac{\sigma_1 - \sigma_3}{P_a} = B \left[ \frac{\sigma_1 + 2\sigma_3}{P_a} \right]^\alpha 
\]

where, \( B \) is a non-dimensional parameter based on material characteristics of the rockfill material. \( \alpha \) is non-dimensional parameter dependent on principal stresses at failure and \( P_a \) is atmospheric pressure in the unit of principal stresses.

Parameter \( \alpha \) can be determined by plotting \((\sigma_1 + 2\sigma_3)/P_a \) \( v/s \) \((\sigma_1 - \sigma_3)/P_a\) using the laboratory test results. Total nine project materials viz. Noa Dehing dam and Lower Jhelum Project (Honkanadavar 2010) and from Ranjit Sagar dam, Tehri dam (old Dobatta and new Dobatta quarries), Western Yamuna Canal (Bridge site and Silt Ejector site), Kol dam and Shah Nehar projects (Abbas 2003) have been considered and tested for determining the \( \alpha \)-value. The value of \( \alpha \) varies from 0.907 to 0.9421 for all the projects and \( \max_d \) tested for 87% and 75% RD. Since the variation of \( \alpha \)-value is marginal, the average value of \( \alpha = 0.9279 \) has been considered in the analysis.

The parameter \( B' \) has been related to the basic characteristics of rockfill material viz. UCS, UVC and RD. The relationship of \( B' \) with basic characteristics of the riverbed rockfill material has been proposed as

\[
B' = C (\text{UCS})^{p_1} (\text{UVC})^{p_2} (\text{RD})^{p_3}
\]

where, \( C \) is coefficient and \( p_1 \), \( p_2 \) and \( p_3 \) are exponents. \( P \) is normalized UCS value as the ratio of UCS of the material to the maximum UCS among all the above mentioned nine project materials considered in the analysis.

The coefficient and exponents have been obtained from the data of above mentioned nine projects riverbed rockfill material with \( \max_d \) of 4.75, 10, 19, 25, 50 and 80 mm for Noa Dehing dam tested with \( \sigma_3 \) varying from 0.2 to 0.8 MPa and 87% and 75% RD. Other projects riverbed rockfill materials have been tested for \( \max_d \) of 25, 50 and 80 mm with \( \sigma_3 \) varying from 0.3 to 1.4 MPa and 87% RD. A FORTRAN computer programme has been developed and used to find out \( C \) and \( p_1 \), \( p_2 \) and \( p_3 \) using least squares fitting method as

\[
B' = 0.995 (\text{UCS})^{0.218} (\text{UVC})^{0.164} (\text{RD})^{0.351}
\]

Substituting the values of normalized UCS (\( \text{UCS}_{\max} = 168.68 \) MPa), UVC and RD in Eq. (4), determined the value of \( B' \) for any \( \max_d \). Then substituting the values of \( B' \) and \( \alpha \) in Eq. (2), the major principal stress (\( \sigma_s \)) at failure for any \( \sigma_3 \) has been determined. Using \( \sigma_1 \) and \( \sigma_3 \), \( \phi \)-value is determined.

The shear strength parameter, \( \phi \) has been predicted for the Noa Dehing dam riverbed rockfill material using the proposed strength law and compared with the experimental values (Table 2). From the comparison, it is observed that both predicted and experimental \( \phi \)-values match closely. From the table, it is observed that the percentage error for \( \max_d \) of 4.75 mm to 80 mm varies from -0.68 to -13.22 and -0.50 to 14.60 for 87% and 75% RD respectively. Therefore, the proposed strength law can be adopted to predict the \( \phi \) of riverbed rockfill material for any \( \max_d \).
The strength law has been used to predict the strength parameter of Noa Dehing dam site prototype rockfill material. For the prototype rockfill material, the value of UVC for $d_{\text{max}}$ of 600 mm has been obtained using the Eq. (1) as 0.2846. The value of $P$ equal to 0.5058 is constant for all $d_{\text{max}}$ of Noa Dehing dam material.

Table 2: Comparison of $\phi$-Values

<table>
<thead>
<tr>
<th>$d_{\text{max}}$ (mm)</th>
<th>87% RD</th>
<th>75% RD</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\phi$ (Exp.) (Deg.)</td>
<td>$\phi$ (Pred.) (Deg.)</td>
</tr>
<tr>
<td>4.75</td>
<td>36.3</td>
<td>41.1</td>
</tr>
<tr>
<td>10</td>
<td>38.6</td>
<td>40.7</td>
</tr>
<tr>
<td>19</td>
<td>39.9</td>
<td>40.1</td>
</tr>
<tr>
<td>25</td>
<td>40.8</td>
<td>40.0</td>
</tr>
<tr>
<td>50</td>
<td>42.5</td>
<td>39.5</td>
</tr>
<tr>
<td>80</td>
<td>43.9</td>
<td>38.9</td>
</tr>
</tbody>
</table>

Following the procedure explained earlier, the $\phi$-value based on index properties has been predicted for prototype riverbed rockfill material of Noa Dehing dam material for $d_{\text{max}}$ of 600 mm and is equal to 43.1$^\circ$ for 87% RD. Using existing extrapolation method based on power law (Venkatachalam 1993, Varadarajan 2003), the $\phi$-value has been predicted as 50.6$^\circ$ for 87% RD. Similarly, the $\phi$-value of prototype rockfill material for 75% RD was predicted by strength law and power law and are equal to 41.2$^\circ$ and 47.6$^\circ$ respectively. The comparison of $\phi$-value of two methods for 87% RD has been presented in Fig. 4.

4. CONCLUSIONS

The riverbed rockfill material from Noa Dehing dam site, Arunachal Pradesh has been considered in the present research work. The material has been modelled into $d_{\text{max}}$ of 4.75, 10, 19, 25, 50 and 80 mm and tested in the laboratory under drained triaxial test conditions for different confining pressures varying from 0.2 to 0.8 MPa and RD of 87% and 75%. The index properties viz. UCS, UVC and UVC have been determined.

Strength law has been developed to relate the shear strength parameter with index properties viz. UCS, UVC and RD of the riverbed rockfill material. The predicted and experimental $\phi$-values were compared and observed that both values match closely.

The $\phi$-value of prototype riverbed rockfill material was predicted using the proposed strength law and compared with the $\phi$-value predicted by using existing extrapolation technique (Power law) based on $d_{\text{max}}$. From the comparison, it is observed that $\phi$-value matches closely for both methods. The advantage of the proposed method is to determine $\phi$-value using index properties viz. UCS, UVC and RD without conducting triaxial tests on rockfill materials. Therefore, it is believed that the proposed method is more realistic, economical, can be used where large size triaxial testing facilities are not available and quick to determine $\phi$-value using index properties.

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