Prediction of shear strength parameter for prototype rock fill material using index properties

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Abstract

Rock fill materials are being used widely in the construction of rock fill dams to harness natural river water because of their inherent flexibility, capacity to absorb large seismic energy and adoptability to various foundation conditions. Riverbed and quarried rock fill materials were obtained from Kalai dam project, Arunachal Pradesh. The maximum particle size of the material used in the dam is 600 mm. For testing, the size is scaled down to 25, 50 and 80 mm maximum particle size (d_{max}) using parallel gradation technique for both materials. Drained triaxial tests are carried out with a specimen size of 381 mm diameter and 813 mm height with varying confining pressure (σ_3) from 0.6 to 1.4 MPa. All the d_{max} are tested for 87% relative density (RD). The index properties of the rock fill materials viz. unconfined compressive strength (UCS) and uncompacted void content (UVC) are determined.

Stress-strain-volume change behaviour of the modeled rock fill material is studied and presented. The shear strength parameter, angle of internal friction (ϕ) is determined for all the d_{max} of modelled rock fill materials tested with 87% RD. Strength law has been developed to determine the failure stresses using index properties of rock fill materials viz. UCS, UVC and RD and then ϕ-values are predicted for both modeled rock fill materials satisfactorily. For both riverbed and quarried rock fill material, the ϕ-value of the prototype rock fill material is predicted using the proposed strength law. The predicted ϕ-value of both prototype rock fill materials is compared with the ϕ-value predicted by commonly used extrapolation technique (power law which requires laboratory triaxial test results) based on d_{max} and found that ϕ-value match closely. Therefore, it is believed that the proposed strength law is more realistic, economical, can be used where large size triaxial testing facilities are not available and quick to determine ϕ-value using index properties.

1. Introduction:

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

Rock fill materials consist of maximum particle size (d_{max}) up to 1200 mm. Rock fill material with such a large particle size is not feasible to test in the laboratory. Some kind of modeling 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 both riverbed and quarried rock fill material has been reported by number of researchers. Marsal (1967), Marachi et al. (1969), Gupta (2000), Abbas (2003), Abbas et al. (2003), CSMRS (2012), Honkanadavar (2010), Honkanadavar et al. (2012), Honkanadavar and Sharma (2013) and Honkanadavar et al. (2014) have performed laboratory tests on both rock fill 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 for both materials. The volume change at failure increases with increase in confining pressure (σ_3) and d_{max} for both rock fill materials. They also concluded that the shear strength parameter, angle of internal friction, ϕ increases with increase in d_{max} for all the riverbed rock fill materials. However, they concluded that the angle of internal friction, ϕ decreases with increase in d_{max} for all the quarried rock fill material.

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

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

2. Experimental Investigations and Discussions:

2.1 Material Used:

To carry out this research work, riverbed and quarried blasted rock fill material from Kalai dam project, Arunachal Pradesh has been used. The rock type is Quartzite Schist, fine grained textured, inequigranular rock and gray in colour.

The d_{max} proposed in the construction of the Kalai dam is 600 mm. The material has been modeled to three d_{max} (25, 50 and 80 mm) using parallel gradation technique as shown in figure 1 & 2 to test in the large size triaxial specimen of size 381 mm diameter and 813 mm height.

2.2 Experimental Programme:

2.2.1 Determination of Index Properties:

It is known that the shear strength of granular materials is dependent on RD, σ_3, individual particle strength, d_{max}, shape, surface texture and mineralogy.

The individual rock fill particle strength can be represented by UCS of the rock from which rock fill 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 rock fill material is shown in figure 3.

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

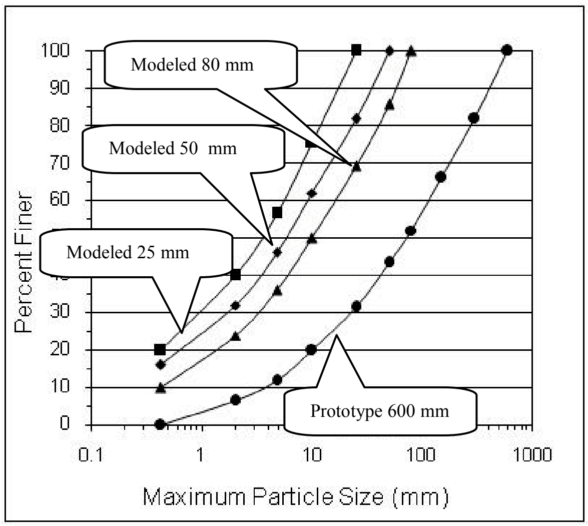


Figure 1 Prototype and Modeled Gradation Curves for Riverbed Rock fill Material

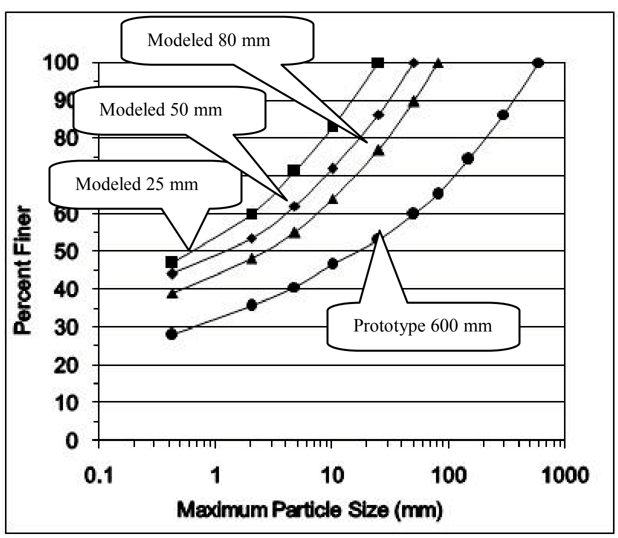


Figure 2 Prototypes and Modeled Gradation Curves for Quarried Rock fill Material

Three modeled rock fill materials of d_{max} = 4.75, 10 and 19 mm were obtained using parallel gradation technique and they were tested to determine the UVC for both material. The d_{max} v/s UVC has been plotted on semi-log graph and then the UVC for 25, 50, 80 and 600 mm d_{max} is determined for both materials using a best fit linear extrapolation as

For riverbed rock fill material:

$$UVC = -0.035\ln (d_{max}) + 0.513 \qquad (1)$$

For quarried rock fill material

$$UVC = -0.037\ln (d_{max}) + 0.538 \qquad (2)$$

The determined index properties are given in Table 1.

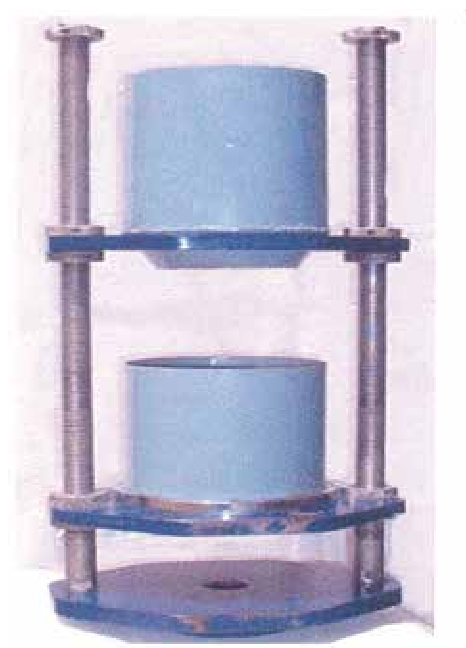


Figure 3 Uncompacted Void Content Test Apparatus

2.2.2 Drained Triaxial Test:

Consolidated drained triaxial tests have been conducted on the modeled rock fill materials with confining pressure varying from 0.6 to 1.4 MPa for 87% RD at Central Soil and Materials Research Station (CSMRS), New Delhi. The stress-strain volume change behaviour of riverbed and quarried modeled rock fill material for 87% RD has been presented in figure 4 and 5 respectively. From the stress-strain plots, it is observed that the behaviour is non-linear, inelastic and stress level dependent for both materials. The deviatoric stress and axial strain at failure increases with increase in d_{max} and σ_3 for both materials. The volume change behavior shows compression during the initial part of shearing and dilation with further shearing which decreases with increase in d_{max} and σ_3 for both materials. The volumetric strain at failure increases with d_{max} and σ_3 for both materials.

Normal stress v/s shear stress was plotted for both materials and shear strength parameter, ϕ is determined for all the d_{max} tested with 87% RD. The experimental ϕ-values are given in table 1. The typical normal stress v/s shear stress plot is presented in figure 6.

3. Prediction of Shear Strength Parameter using Index Properties:

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

$$\frac{\sigma_1 - \sigma_3}{P_a} = B'\left[\frac{\sigma_1 + 2\sigma_3}{P_a}\right]^{\alpha'} \quad (3)$$

Where, B' is a non-dimensional parameter based on material characteristics of the rock fill material, α' is non-dimensional parameter dependent on principal stresses at failure and P_a is atmospheric pressure in the unit of principal stresses.

Table 1
Properties of Riverbed and Quarried Rock fill Materials

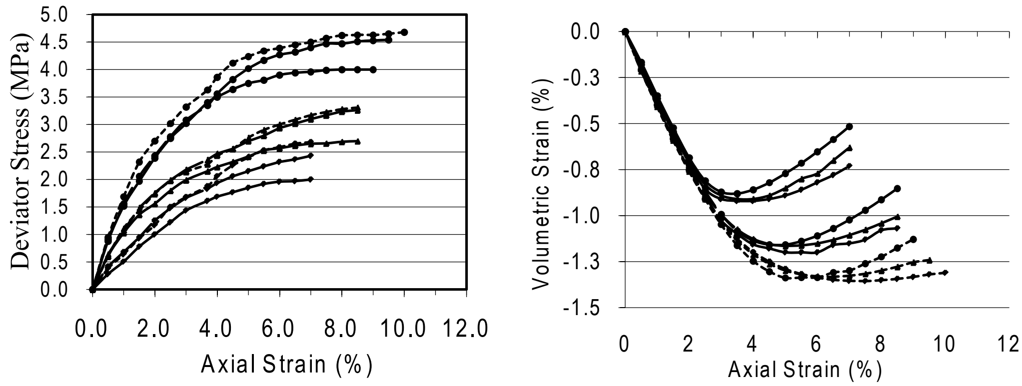
Properties	d_{max} (mm)					
	4.75	10	19	25	50	80
UVC (Riverbed)	0.35	0.33	0.31	0.29	0.28	0.26
UVC (Quarried)	0.42	0.40	0.39	0.38	0.37	0.36
UCS (MPa) (Riverbed)	← 83.38 →					
UCS (MPa) (Quarried)	← 61.85 →					
ϕ (degree) (Riverbed)	-	-	-	36.1	38.8	39.4
ϕ (degree) (Quarried)	-	-	-	44.9	44.0	43.2

Parameter α' 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 ten project materials viz. Noa Dehing dam and Lower Jehlum Project Ranjit Sagar dam, Tehri dam (old Dobatta and new Dobatta quarries), Western Yamuna Canal (Bridge site and Silt Ejector site), Kol dam, Shah Nehar projects (Honkanadavar 2010) and Kalai dam project (CSMRS 2012) have been considered and tested for determining the α' value. The value of α' varies from 0.901 to 0.935 for all the projects and d_{max} tested for 87% RD. Since the variation of α' value is marginal, the average value of α'=0.918 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 and quarried rockfill material has been proposed as

$$B' = C(P)^{p_1}(UVC)^{p_2}(RD)^{p_3} \quad (4)$$

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 ten project materials considered in the analysis.



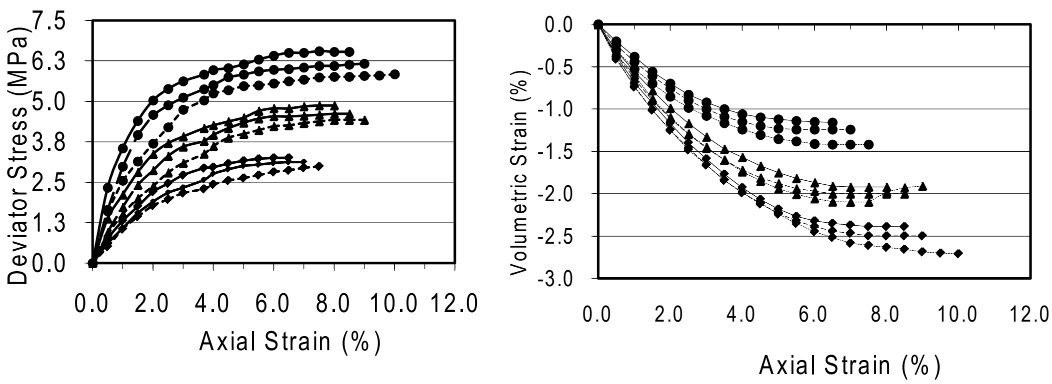
(a) Stress-Strain Behaviour (b) Volume Change Behaviour

Combined legend for Fig 4 (a) and 4 (b)

25 mm 50 mm - - - 80 mm

0.6 MPa 1.0 MPa 1.4 MPa

Figure 4 Stress-Strain-Volume Change Behaviour of Riverbed Rock fill Material



(a) Stress-Strain Behaviour (b) Volume Change Behaviour

Combined legend for Fig 5 (a) and 5 (b)

25 mm 50 mm - - - 80 mm

0.6 MPa 1.0 MPa 1.4 MPa

Figure 5 Stress-Strain-Volume Change Behaviour of Quarried Rock fill Material

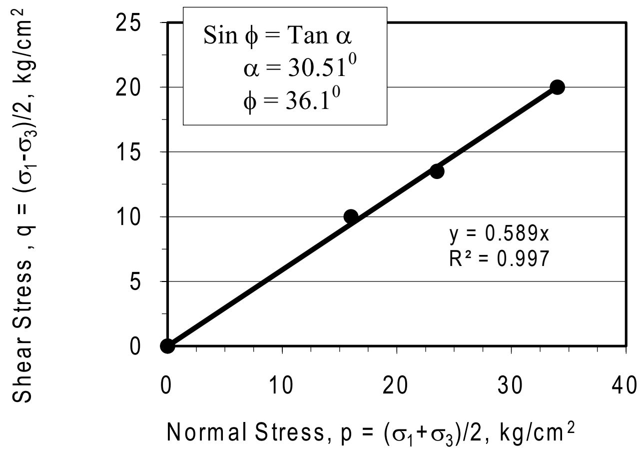


Figure 6 Typical normal stress v/s shear stress plot for 25 mm d_{max} of riverbed rockfill material

The coefficient and exponents have been obtained from the data of above mentioned ten projects rockfill material with d_{max} of 4.75, 10, 19, 25, 50 and 80 mm for Noa Dehing dam tested with σ_3 varying from 0.2 to 0.8 MPa and 87% and 75% RD. Other projects rockfill materials have been tested for d_{max} of 25, 50 and 80 mm with σ_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 for riverbed and quarried rockfill material as

For riverbed rock fill material

$$B' = 0.981(P)^{0.202}(UVC)^{0.155}(RD)^{0.345} \quad (5)$$

For quarried rock fill material

$$B' = 1.455(P)^{0.061}(UVC)^{0.610}(RD)^{-0.083} \quad (6)$$

Substituting the values of normalized UCS (UCS_{max}= 168.68 MPa and 105.24 MPa for riverbed and quarried rock respectiely), UVC and RD in Eq. (5 and 6), determined the value of B' for any d_{max} of riverbed and quarried rockfill material. Then substituting the values of B' and α' in Eq. (3), the major principal stress (σ_1) at failure for any σ_3 has been determined. Using σ_1 and σ_3, ϕ-value is determined for all the d_{max} of both materials.

The shear strength parameter, ϕ has been predicted for the Kalai dam riverbed and quarried 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 ϕ-values match closely. Therefore, the proposed strength law can be adopted to predict the ϕ value of riverbed and quarried rockfill material for any d_{max}.

The strength law has been used to predict the strength parameter of Kalai dam riverbed and quarried prototype rockfill material. For the prototype rockfill material, the value of UVC for d_{max} of 600 mm has been obtained using the Eq. (1 and 2) as 0.2446 and 0.3216 for riverbed and quarried rockfill material respectively. The value of P equal to 0.51 and 0.62 for riverbed and quarried rock respectively.

Table 2
Comparison of ϕ-Values

d_{max} (mm)	Riverbed			Quarried rock fill material		
	ϕ (Exp.) (deg.)	ϕ (Pred.) (deg.)	. Err.	ϕ (Exp.) (deg.)	ϕ (Pred.) (deg.)	. Err.
25	36.1	36.5	1.1	44.9	43.3	3.5
50	38.8	40.2	3.6	44.0	42.1	4.3
80	39.4	42.8	8.6	43.2	40.5	6.3

Following the procedure explained earlier, the ϕ-value based on index properties has been predicted for prototype riverbed and quarried rockfill material of Kalai dam for d_{max} of 600 mm and is equal to 46.4^o and 40.4^o for riverbed and quarried rockfill material respectively tested with 87% RD. Using existing extrapolation method based on power law (Venkatachalam 1993, Varadarajan 2003), the ϕ value has been predicted for all the d_{max} of both materials. From the comparison of ϕ-value determined by strength law and Power law with experimental ϕ-values, it is observed that both values match closely.

4. Conclusions:

The riverbed and quarried rockfill material from Kalai dam, Arunachal Pradesh has been considered in the present research work. Both materials have been modeled into d_{max} of 25, 50 and 80 mm and tested in the laboratory under drained triaxial test conditions for different confining pressures varying from 0.6 to 1.4 MPa and RD of 87%. The index properties viz. UCS 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 and quarried rockfill materials. The predicted and experimental ϕ-values were compared and observed that both values match closely.

The ϕ-value of prototype riverbed and quarried rockfill material was predicted using the proposed strength law and compared with the ϕ-value predicted by using existing extrapolation technique (Power law) based on d_{max}. From the comparison, it is observed that the ϕ-value match closely. The advantage of the proposed strength law is to determine ϕ-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 ϕ-value using index properties.

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