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Prediction of Shear Strength Parameter using Basic Index Properties and Modeling the Behaviour of Prototype Riverbed Rockfill Material

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Abstract. In the present study, to verify the developed methods, modeled riverbed rockfill material from Tehri dam old dobatta borrow area, Uttarakhand, India has been considered, tested and studied the material behaviour. Using the developed methods ϕ, E and ν are predicted for all the tested modeled rockfill and compared with the test results. From the comparison, it is observed that both results match closely. Therefore, ϕ, E and ν value of the prototype rockfill material are predicted using the proposed methods for designing the rockfill dam. The advantage of the proposed methods is to determine the material parameters using index properties viz. UCS, UVC and RD without conducting large size triaxial shear tests. Developed methods are more realistic, economical, can be used where large size triaxial testing facilities are not available. A quarter of the triaxial specimen with axisymmetric geometry has been modeled using hierarchical single surface (HISS) constitutive model and DSC-SST2D computer software. Stress-strain-volume change behavior of tested modeled rockfill was back predicted and compared with the experimental results. From the comparison, it is observed that both results match closely. Predicted the stress-strain-volume change behavior for prototype Rockfill material and it is observed that its behavior also follows similar trend as that of modeled Rockfill material. Therefore, it is proposed that HISS constitutive model can be used to characterize the riverbed rockfill material successfully.

Keywords: Riverbed, Triaxial, Behaviour, Predicted, Constitutive Model.

1 Introduction

Rockfill material is being used extensively in the construction of earth core rockfill dam (ECRD) and concrete faced rockfill dam (CFRD) because of its inherent flexibility, capacity to absorb large seismic energy and adoptability to various foundation conditions. The use of modern earth and rock moving equipments and use of locally available rockfill material make such dams economical.

Rockfill material consists of maximum particle size (d_{max}) up to a meter in diameter. Rockfill material with such a large particle size is not feasible to test in the laboratory. Therefore, modeling techniques are being used to down size the particles so that the specimens prepared with smaller size particles can be prepared and tested in the laboratory. Among all existing modeling techniques, the parallel gradation technique (Lowe 1964) is most commonly used. The behaviour of riverbed rockfill material has been studied by number of researchers. Marsal (1967), Marachi et al. (1969), Gupta (2000), Abbas (2003), Abbas et al. (2003), Honkanadavar (2010), Honkanadavar and Sharma (2010, 2011, 2012, 2013, 2014 and Honkanadavar 2015, 2016, 2017) have performed laboratory tests on riverbed rockfill material 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 increases with increase in confining pressure (σ_3) and d_{max} at failure.

Stress-strain-volume change behaviour of riverbed rockfill material has been characterized by many researchers using hierarchical single surface (HISS) models (Varadarajan et al. 2002, 2003 and Abbas 2003). From the laboratory test results, they determined the material parameters and back predicted the stress-strain-volume change behaviour using HISS model and compared with the observed behaviour. From the predicted and observed results they found that both observed and predicted results match closely. Their prediction is based on only two index properties i.e. uniaxial compressive strength (UCS) and uncompacted void content (UVC).

This paper deals with the testing of riverbed rockfill material obtained from Tehri dam site, Uttarakhand and study its stress-strain-volume change behaviour tested with 87% relative density. Tests were also conducted to determine the index properties of viz. UCS and UVC. In the present study the third index property i.e. relative density (RD) is also considered for analyses. Procedures were developed to predict the material parameters using the basic index properties of the rockfill material where UCS represents the strength of the rock from which rockfill materials are derived and it is independent of d_{max}. UVC includes the effect of gradation, shape, size and surface texture of the rockfill materials and it is dependent on d_{max}. RD represents the relative compactness of the rockfill materials. Total nine projects materials were considered to develop procedures and predict the strength and elastic material parameters (Honkanadavar 2010). Using the developed procedures, material parameters were predicted and compared with the laboratory test results. Simulated the triaxial test specimen and back predicted the stress-strain-volume change behaviour for all the d_{max} of Tehri dam using HISS model. The predicted stress-strain-volume change behaviour of modeled rockfill material is compared with observed behaviour of laboratory tests. Developed procedures were also used to predict the material parameters for the prototype rockfill material and back predicted its stress-strain-volume change behaviour using HISS model.

2 Experimental Investigations and Discussion

2.1 Material used

In the present study, rockfill material from Tehri dam site (old dobatta borrow area), Uttarakhand has been used. The rock type is quartzite, tabular grains, equigranular, granoblastic in texture, leucocratic grey in colour, metamorphosed from sedimentary rock. The d_{max} proposed in the construction of shell portion of Tehri dam is 600 mm. Field prototype grain size distribution tests were conducted and an average prototype gradation curve with d_{max} of 600 mm was obtained and presented. Sizes of different percent finer i.e. for d_{10}, d_{30}, d_{60} and average particle size d_{50} were calculated from the prototype gradation curve and determined coefficient of uniformity (C_u) and coefficient of curvature (C_c) were determined and presented in Table 1.

Table 1. Cu and Cc for Prototype Gradation Curve

Sizes for different percent finer (mm)	C_u (d_{60}/d_{10})	C_c ($d_{30}^2/(d_{60}Xd_{10})$)	d_{50} (mm)
d_{10} = 1.5 d_{30} = 20 d_{60} = 150	2.67	1.77	85

The prototype rockfill material has been modeled into d_{max} of 25, 50 and 80 mm using parallel gradation technique as shown in Fig. 1 for testing in the large size triaxial specimen of size 381 mm diameter and 813 mm height.

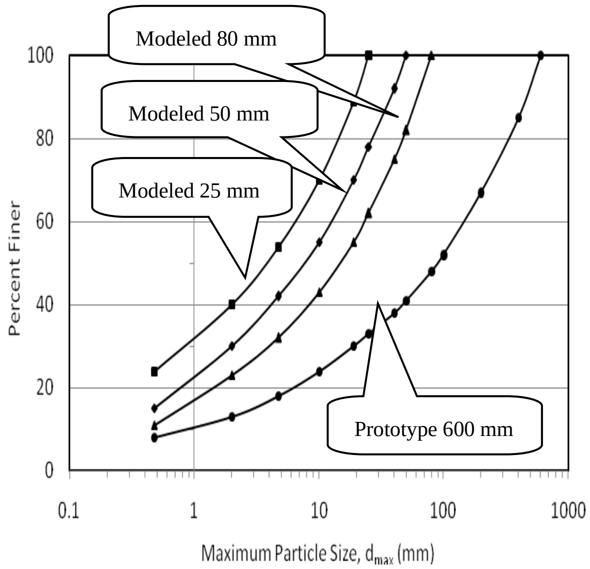


Fig. 1. Prototype and modeled Grain Size Distribution Curves

2.2 Experimental programme

Determination of index properties: From the literature, it is known that the behaviour of rockfill material is dependent on RD, confining pressure (σ_3), individual particle strength, d_{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 from Tehri dam site as per IS: 1943-1979 and average value of UCS is obtained as 125.36 MPa.

Shape, size, surface texture and gradation of aggregates are represented by a basic characteristic known as UVC for coarse material (ASTM C1252-98, Alhrich 1996). The apparatus has been modified and fabricated to determine UVC for rockfill material (Honkanadavar 2010).

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

Three modeled rockfill materials of d_{max} = 4.75, 10 and 19 mm were obtained using parallel gradation technique and they were tested to determine the UVC. 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 using a best fit linear extrapolation as

$$UVC = -3.83\ln(d_{max}) + 44.85 \quad (1)$$

The determined index properties are given in Table 2.

Determination of modulus of elasticity and poisson's ratio: The deformability characteristics viz. modulus of elasticity of intact rock (E_{ir}) and Poisson's ratio of intact rock (ν_{ir}) were determined for rock cores of NX size for conducting laboratory tests using uniaxial compression testing machine (Brown 1981). During the test, the axial load, axial strain and lateral strains were measured till the rock core specimen fails. Axial load v/s axial strain and axial load v/s lateral strain graphs were plotted and the modulus of elasticity and Poisson's ratio were determined (Honkanadavar 2010). The E_{ir} is the slope of the tangent on axial stress-axial strain curve drawn at 50% failure stress and ν_{ir} is determined as the ratio of lateral strain to the axial strain at 50% failure stress (IS 9221-2010; ASTM D7012-04). The modulus of elasticity and Poisson's ratio of intact rock are given in Table 2.

Drained triaxial test: Consolidated drained triaxial tests have been conducted on the modeled rockfill material with σ_3 varying from 0.4 to 1.2 MPa at Central Soil and Materials Research Station (CSMRS), New Delhi.

Stress-strain-volume change behaviour for all the d_{max} is studied. From the stress-strain plots, it is observed that the behaviour is non-linear, inelastic and stress level dependent. 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. Typical stress-strain-volume change behaviour of 80 mm modeled rockfill material tested with 87% RD has been presented in Fig. 2.

Table 2. Index Properties of Rockfill Material

Properties	RD (%)	d_{max} (mm) 4.75	10	19	25	50	80
UVC (%)		38.9	36.0	33.6	32.5	29.9	28.1
UCS (MPa)		← 125.36 →					
ϕ (Degree)	87				36.2	37.6	39.2
E_{ir} (MPa)		← 67800 →					
ν_{ir}		← 0.31 →					

Mean stress v/s deviatoric stress was plotted and shear strength parameter, ϕ is determined for all the d_{max} tested and presented in Table 2. Using the standard procedures, elastic parameters viz. modulus of elasticity, E and Poisson's ratio, ν are determined from the laboratory test results and presented in Table 3.

3 Prediction of Material Parameters using Index Properties

Following procedures have been developed to predict the E and ν and the non-dimensional parameter B′ of the modeled rockfill materials using index property.

$$E / E_{ir} = C(UVC)^{T_1} (\sigma_3 / P_a)^{T_2} \quad (2)$$

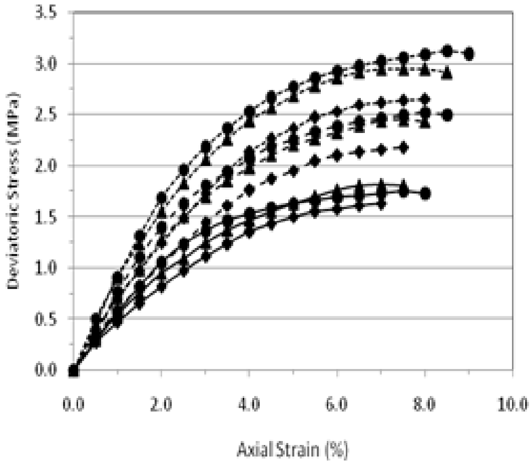
$$\nu / \nu_{ir} = C'(UVC)^{T_3} (\sigma_3 / P_a)^{T_4} \quad (3)$$

where, E and ν are the modulus of elasticity and Poisson's ratio respectively for rockfill and E_{ir} and ν_{ir} are the modulus of elasticity and Poisson's ratio respectively for intact rock from which rockfill materials are derived. C and C′ are the coefficients and T_1, T_2, T_3 and T_4 are the exponents.

From the literature, it is known that the factors viz. RD, UCS, gradation, d_{max}, particle shape and surface texture affect the shear strength parameter of the granular materials. Therefore, to incorporate these factors, a non-dimensional parameter B′ has been related to the index properties viz. UCS, UVC and RD. The relationship of B′ with index properties is proposed as

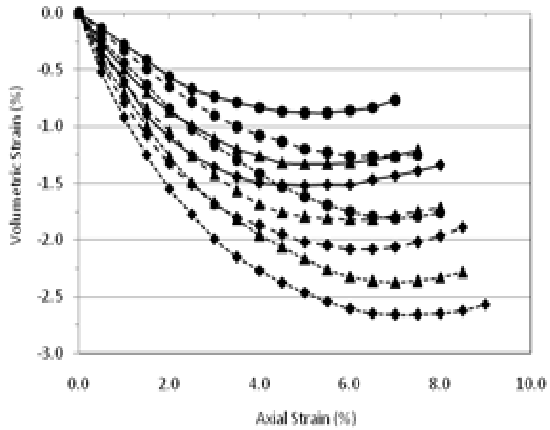
$$B' = D(P)^{p_1} (UVC)^{p_2} (RD)^{p_3} \tag{4}$$

where, P is the normalized UCS (Ratio of UCS of the material to the maximum UCS of the material among all the rockfill materials i.e. UCS/UCS_{max}) and D is the coefficient.



(a) Stress-Strain Behaviour

Combined legend for Fig 2 (a) and 2 (b)
● 25 mm ▲ 50 mm ◆ 80 mm
—— 0.4 MPa - - - 0.8 MPa ········ 1.2 MPa



(b) Volume Change Behaviour

Fig. 2. Stress-Strain-Volume Change Behaviour for 25 mm, 50 mm and 80 mm d_{max}.

Using the developed FORTRAN computer programme, the coefficients and exponents in Eqs. 2-4 are determined adopting a least squares fitting technique. For determining the coefficients and exponents, total nine projects riverbed rockfill materials from India and abroad have been considered (Honkanadavar, 2010). Substituting the values of coefficients and exponents in Eqs. 2-4 becomes

$$E/E_{ir} = 1.839\ \mathrm{x}10^{-4}(UVC)^{-0.991}(\sigma_3/P_a)^{0.52} \quad (5)$$

$$\nu/\nu_{ir} = 2.04(UVC)^{0.615}(\sigma_3/P_a)^{-0.031} \quad (6)$$

$$B' = 0.995(UCS/UCS_{max})^{0.218}(UVC)^{0.164}(RD)^{0.351} \quad (7)$$

Substituting the values of E_{ir}, UVC, ν_{ir} and σ_3, E and ν of rockfill material can be determined for any d_{max} using Eqs. 5-6. Substituting the normalized UCS (UCS_{max}= 125.36 MPa), UVC and RD in Eq. 7, B' value can be determined for any d_{max}. Substituting B' in the proposed strength law (Honkanadavar 2010), the major principal stress (σ_1) at failure is determined for the corresponding minor principal stress (σ_3). Plotting mean stress (σ_1+2σ_3)/3 v/s deviator stress (σ_1-σ_3), the angle of shearing resistance, ϕ is determined for all the d_{max} tested. Using Eqs 5-6, Elastic parameters were predicted for all the d_{max} tested. Determined and predicted ϕ, E and ν values for all the d_{max} tested are presented in Table 3. From the comparison, it is observed that both determined and predicted results match closely. Therefore, these procedures have been adopted to determine the material parameters of modeled and prototype (600 mm) rockfill material of Tehri dam.

Table 3. Determined and Predicted Material Parameters

d_{max} (mm)	σ_3 (MPa)	ϕ (degree)		E (MPa)		ν (Poisson's Ratio)	
		Det	Pred	Det	Pred	Det	Pred
25	0.4	36.2	36.1	69.83	76.82	0.303	0.282
	0.8			105.64	110.15	0.303	0.276
	1.2			128.36	136.00	0.303	0.273
50	0.4	37.6	37.9	79.52	83.57	0.298	0.279
	0.8			114.78	119.83	0.298	0.273
	1.2			136.97	147.96	0.298	0.270
80	0.4	39.2	40.1	82.37	88.88	0.287	0.277
	0.8			116.92	127.44	0.287	0.271
	1.2			155.3	157.36	0.287	0.268
600	0.4		45.4	-	122.24	-	0.268
	0.8			-	175.28	-	0.262
	1.2			-	216.42	-	0.259

3.1 Prediction of stress-strain-volume change behaviour using HISS model

Hierarchical Single Surface (HISS) model: In this model, a unique and continuous yield function is used that leads to the failure when an ultimate condition is reached. The model is based on associative plasticity and isotropic hardening. The yield function for the model is given in Eq. 8.

$$F = \left[\frac{J_{2D}}{P_a^2}\right] - \left[-\alpha\left[\frac{J_1}{P_a}\right]^n + \gamma\left[\frac{J_1}{P_a}\right]^2\right](1-\beta S_r)^m \tag{8}$$

where,

$$S_r = \frac{\sqrt{27}}{2}\frac{J_{3D}}{J_{2D}^{1.5}} \tag{9}$$

P_a is the atmospheric pressure; γ, β and n are material parameters; α is the hardening function; J_1 is the first invariant of stress tensor; J_{2D} and J_{3D} are the second and third invariants of deviatoric stress tensors, respectively. Elastic Parameters (E, ν), Ultimate Parameters (m, γ, β), Phase Change Parameter (n), Hardening Parameters (a_1, η_1) and Non-associative parameter (κ) are the input parameters for the HISS model and are determined using the standard procedures (Varadarajan and Desai 1993, Desai 1994, Abbas 2003, Honkanadavar 2010).

Modeling of triaxial testing specimen. In the present study, the triaxial specimen of size 381 mm diameter and 813 mm height has been tested in the laboratory for Tehri dam modeled rockfill material. A quarter of the triaxial specimen with axisymmetric geometry (Fig. 3) has been modelled using disturbed state concept-soil structure two dimensional analysis (DSC-SST2D) computer software for considered riverbed rockfill material.

The triaxial specimen has been modelled by means of single 8-noded isoparametric solid element for DSC-SST2D. The stresses and strains are assumed to be uniformly distributed over this geometry. The bottom and left hand side of the geometry are axis of symmetry (Fig. 3). At these boundaries, the displacements normal to the boundary are restrained and the remaining boundaries are fully free to move.

A triaxial test is simulated in two phases; consolidation and shearing. The consolidation phase is simulated by stress controlled and shearing phase is simulated by strain controlled method. In the first phase, the confining pressure is applied by activating load A and load B by equal amount as shown in Fig. 3.

In the second phase, displacements are reset to zero and the specimen is sheared by strain controlled test up to desired axial strain level while the horizontal load B (confining pressure) is kept constant.

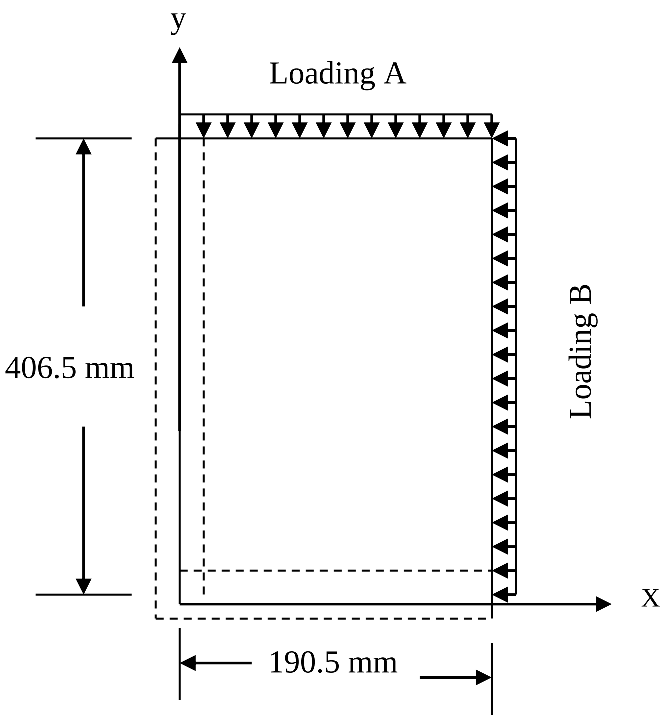


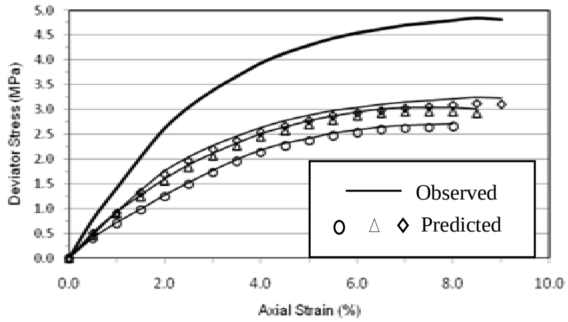
Fig. 3. Simplified Configuration of a Triaxial Test

Stress-strain-volume change behaviour was predicted and compared with the experimental results for all the tested modeled riverbed rockfill materials considered in the present study. A typical observed and predicted stress-strain-volume change behaviour for 25, 50 and 80 mm tested with 1.2 MPa confining pressure is presented in Fig. 4.

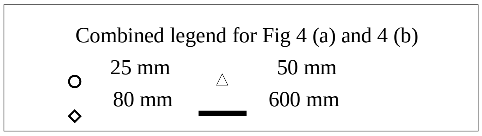
Developed procedures have been used to predict strength and elastic material parameters. Comparing predicted and test results, it is observed that strength and elastic material parameters match closely. Using the predicted material parameters, stress-strain-volume change behaviour of modeled and prototype riverbed rockfill material of Tehri dam (Old Dobatta borrow area) has been back predicted using HISS model for all the d_{max} tested. The predicted behaviour of modeled rockfill material matches closely with the observed behaviour of modeled rockfill material. It is also observed that the predicted behaviour of prototype rockfill material follows similar trend as that of modeled rockfill material. The typical observed and predicted behaviour of modeled rockfill material for different d_{max} and predicted prototype (d_{max} = 600 mm) of Tehri dam project tested with 87% RD and σ_3=1.2 MPa is shown in Fig. 4.

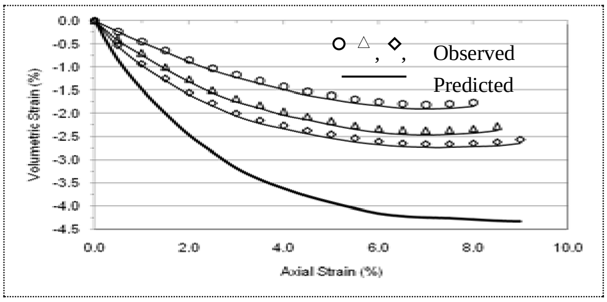
4 Conclusions

The riverbed rockfill material from Tehri dam site, Uttarakhand has been considered in the present study. The material has been modeled into d_{max} of 25, 50 and 80 mm and tested in the laboratory under consolidated drained triaxial test conditions for different confining pressures ranging from 0.4 to 1.2 MPa and 87% RD. The index properties viz. UCS and UVC have been determined.



(a) Stress-Strain Behaviour





(b) Volume Change Behaviour

Fig. 4. Observed and Predicted Stress-Strain-Volume Change Behaviour of different d_{max} tested with 87% RD (σ_3 = 1.2 MPa).

Procedures have been developed using the index properties viz. UCS, UVC and RD to predict the strength, elastic and non-dimensional parameters of the riverbed rockfill material. Developed procedures have been used to predict strength and elastic material parameters. The predicted material parameters were compared with the observed test results and found that both values match closely. Other material parameters were related with the non-dimensional parameter B′ and predicted the values for modeled and prototype material using best fit extrapolation technique.

Using the predicted material parameters, the stress-strain-volume change behaviour of modeled and prototype riverbed rockfill material is predicted using HISS model based on elasto-plasticity. The predicted stress-strain-volume change behaviour of modeled rockfill material is compared with the observed behaviour of modeled material. From the comparison, it is observed that both the results match closely. It is also observed that the predicted behaviour of prototype rockfill material follows similar trend as that of modeled rockfill material. Therefore, this model appears to be suited to characterize the behaviour of riverbed rockfill material. The advantage of the proposed methods is that the developed methods are more realistic, economical, can be used where large size triaxial testing facilities are not available and quick to predict ϕ, E and ν using index properties.

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