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Modeling the Triaxial Behaviour of Alluvial and Quarried Rockfill Materials using Hardening Soil Model

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Abstract. Abstract: Rockfill materials are mainly being used in the construction of rockfill and earth core rockfill dams. In the present study, consolidated drained triaxial tests were conducted with a specimen size of 381 mm diameter and 813 mm height for alluvial and quaried rockfill materials. Studied the stress-strain-volume change behavior for both materials. Index properties viz. uncompacted void content (UVC) and uniaxial compressive strength (UCS) were determined for both materials. An elasto-plastic hardening soil (HS) constitutive model is used to predict the behavior of both modeled rockfill material. Compared the predicted and observed behavior of modelled rockfill material and it is found that both observed and predicted behavior match closely. Procedures were developed to predict the shear strength and elastic parameters of rockfill materials using the index properties viz. UCS, UVC and relative density (RD) and predictions were made satisfactorily. Compared the predicted and experimentally determined shear strength and elastic parameters and it was observed that both values match closely. Then these procedures were extended to predict the elastic and shear strength parameters of large size prototype rockfill materials. Correlations are also developed between index properties and material strength parameters (dilatancy angle, ψ and initial void ratio, e_{init} required for HS model) of modeled rockfill materials and the same are used to predict the strength parameters for the both prototype rockfill materials. Using the predicted material parameters, the behavior of prototype rockfill materials is predicted using HS model. It is observed that the predicted behaviour of prototype rockfill material follows the similar trend as that of modelled rockfill material. The advantage of the proposed methods is that only index properties viz. UCS, UVC, RD and elastic properties of intact rock E_{ir} and ν_{ir} are required to be obtained to determine angle of shearing resistance (ϕ), modulus of elasticity, E_{50}^{ref} and Poisson's ratio, ν of rockfill materials. It is believed that the proposed methods are more realistic, economical, and can be used where large size triaxial testing facilities are not available.

Keywords: *Rockfill, Testing, Behaviour, Modeling, Strength Law, HS Model*.

1 Introduction

Rockfill materials are being used all over the world in the construction of rockfill dams because of their inherent flexibility, capacity to absorb large seismic energy and adaptability to various foundation conditions. Locally available materials and use of modern earth and rock moving equipment make such dams economical as well. Rockfill material consists of gravel, cobbles and boulders obtained either from the natural riverbed or by blasting the rock quarry. Alluvial rockfill materials primarily consist of rounded/sub-rounded shape particles obtained from the natural riverbed. Blasted quarried rockfill material primarily consists of angular/sub-angular shape particles. The factors such as mineral composition, particle size, shape, gradation, relative density (RD), individual particle strength, void content and surface texture of the particles affects the behavior of rockfill materials. Therefore, the understanding and characterization of the behavior of these materials is of considerable importance for the analysis and safe design of the rockfill dams. Prototype rockfill materials consist of maximum particle size (d_{max}) up to 1200 mm. Rockfill 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 available modeling techniques, the parallel gradation technique [1] is most commonly used.

Hyperbolic and elastic models are often adopted to characterize the linear and non-linear behavior of rockfill materials. In recent times, attempts are being made to use advanced constitutive models based on elasto-plastic theory to depict the behavior of rockfill materials. The material parameters required for the constitutive model are determined using the laboratory test results for different d_{max} of modeled rockfill materials. These material parameters are correlated with the index properties of rockfill material viz. uncompacted void content (UVC) and uniaxial compressive strength (UCS). Material parameters for prototype rockfill material of larger size are then determined using a best fit linear extrapolation ([2], [3], [4]).

This paper presents laboratory test results, modeling the behavior of two types of modeled rockfill materials using hardening soil (HS) model and comparison with the observed behavior, proposed procedures to predict the material parameters for prototype rockfill materials using the basic index properties and prediction of prototype material behavior using HS model.

2. Investigations

2.1 Laboratory Tests

2.1.1 Rockfill Materials: Riverbed modeled rockfill material which is rounded to sub-rounded and blasted rockfill material which is angular to sub-angular in shape were collected from two different project sites. Both rockfill materials have been modeled/down sized to six number of d_{max} viz. 4.75, 10, 19, 25, 50 and 80 mm. Parallel gradation technique [1] has been used to model down the d_{max}. The prototype and modeled grain size distribution curves for both materials are shown in Figs.1 and 2.

2.1.2 Index Properties of Rockfill Materials: It is learnt that the shear strength of granular materials is dependent on relative density (RD), confining pressure (σ_3), individual particle strength, d_{max}, shape, surface texture and mineralogy. The individual particle strength is one of the important factors affecting the behavior of the granular materials and it is represented by a parameter known as uniaxial compressive strength (UCS) of the rock from which rockfill material is derived. Three cylindrical specimens of NX size were tested as per the ISRM suggested method [5] for both material and the average value is reported in Table 1 ([2], [3], [4]).

Basic characteristics of rockfill material viz. size, shape, gradation and surface texture of the particles are expressed by a single parameter known as uncompacted void content (UVC) ([6], [7]). The details of test apparatus and procedure to determine UVC is given by ([2], [3], [4]). Determined values of UVC for d_{max} ranging from 4.75 mm to 80 mm are presented in Table 1.

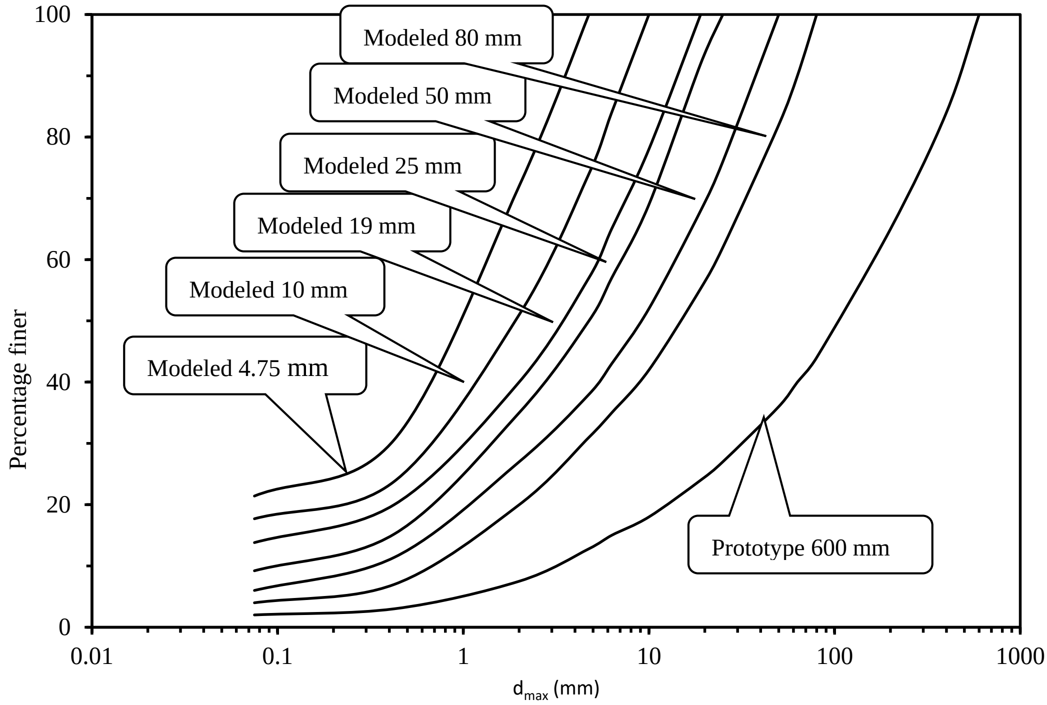


Fig. 1: Grain Size Distribution Curve of Alluvial Rockfill Material

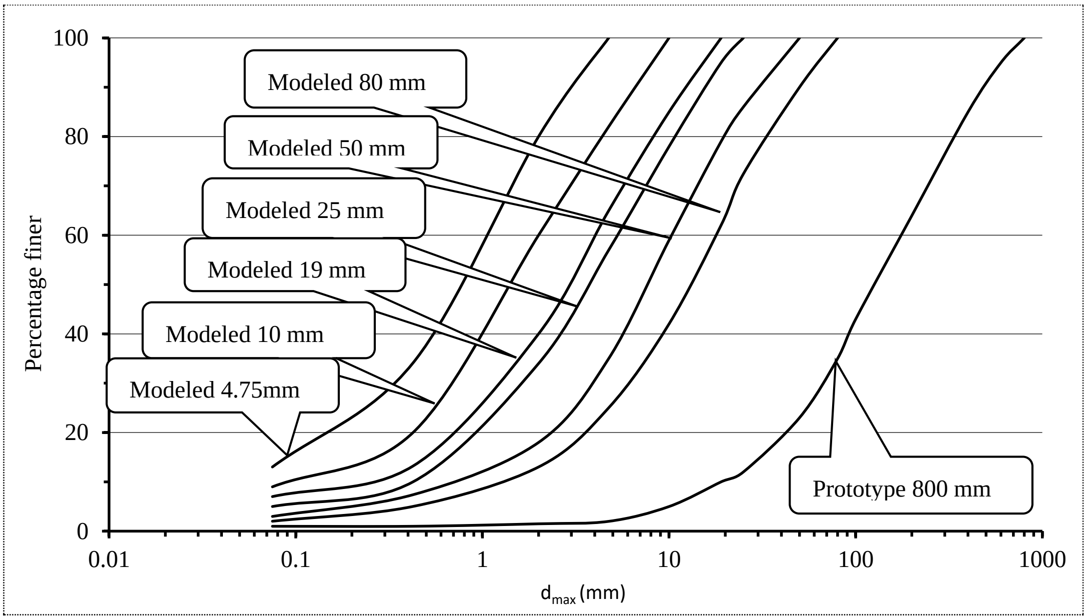


Fig. 2: Grain Size Distribution Curve of Quarried Rockfill Material

Table 1: Index Properties of Alluvial and Quarried Rockfill Materials

Material Type	RD (%)	UCS (MPa)	UVC (%)					
			d_{max} (mm)					
			Experimental				Predicted	
			4.75	10	19	25	50	80
Alluvial	87 & 75	85.32	0.48	0.45	0.43	0.42	0.39	0.37
Blasted Quarried	87 & 75	63.80	0.42	0.41	0.40	0.39	0.38	0.38

2.1.3 Triaxial Tests: Both alluvial and quarried modeled rockfill materials have been tested for d_{max} of 4.75, 10, 19, 25, 50 and 80 mm with the σ_3 varying from 0.2 to 1.6 MPa and 87% and 75% RD. For testing, a dry density corresponding to 87% and 75% RD is adopted [2].

Consolidated drained triaxial tests have been conducted on the modeled rockfill materials at CSMRS**.** Large size triaxial shear test equipment with specimen size of 381 mm diameter and 813 mm height is used for carrying out drained triaxial shear tests [2]. The detailed procedure to conduct the large size triaxial shear test is given by [2] and [4].

From the test results, stress-strain-volume change behaviour is plotted in figures 3 and 4 for alluvial and quarried rockfill materials respectively. From the deviatoric stress-axial strain curves, the major principal stress (σ_1) is determined at failure for a corresponding σ_3. Using σ_1 and σ_3, the shear strength parameter viz. angle of shearing resistance, ϕ is determined using Mohr-Coulomb failure criterion for all the d_{max} of both rockfill materials. The values of ϕ are presented in Table 2**.** From the table it is observed that the ϕ-value increases for alluvial and decreases for blasted quarried rockfill materials with d_{max} and it increases with increase in RD for both alluvial and blasted quarried rockfill materials.

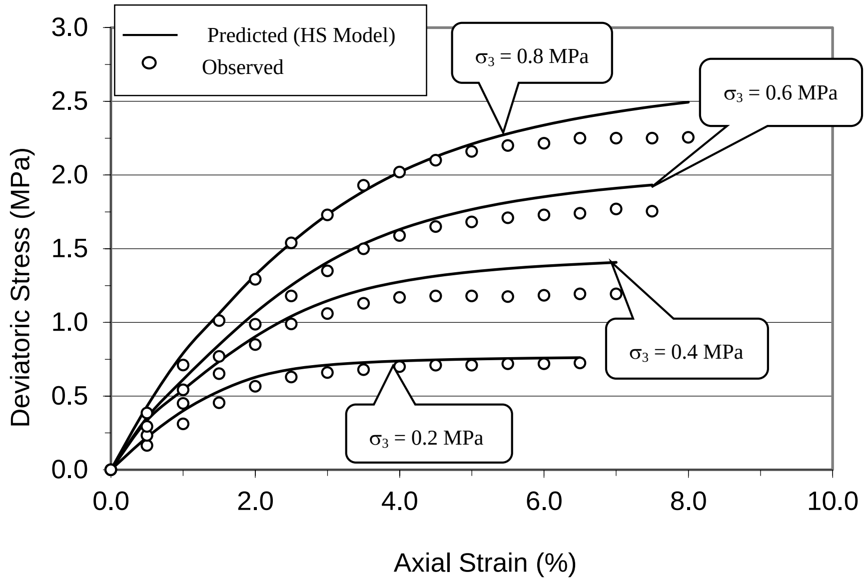
3. Discussion

3.1 Material Parameters

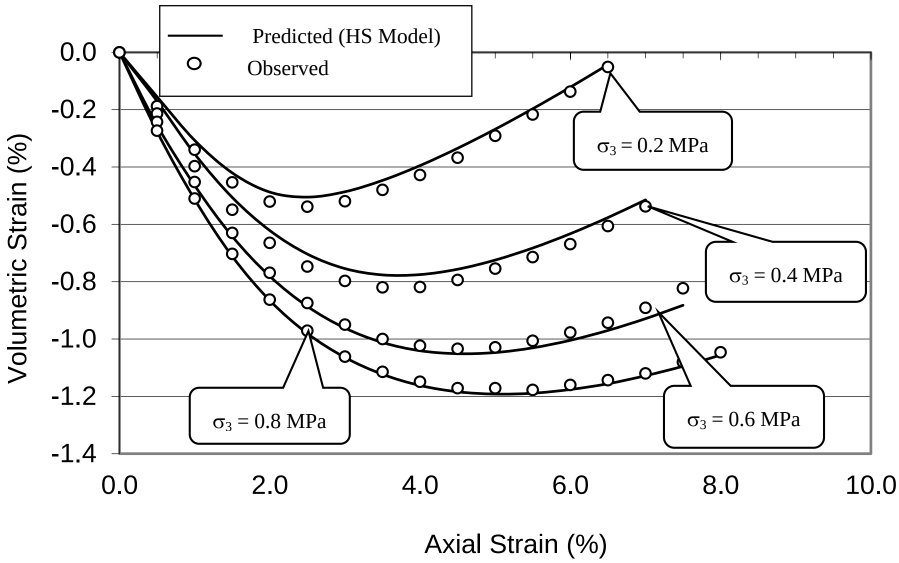
The procedure for the determination of material parameters required in the HS model has been described in detail in various references ([8], [2]). The determined material parameters are presented in Table 2.

3.2 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 all the d_{max} of both modeled rockfill materials. A quarter of the triaxial specimen with axisymmetric geometry [2] has been modeled using PLAXIS computer software for all the d_{max} of both alluvial and quarried rockfill materials. The triaxial specimen has been modeled by means of one hundred two 15-noded triangular elements. 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. At these boundaries, the displacements normal to the boundary are restrained and the remaining boundaries are fully free to move.



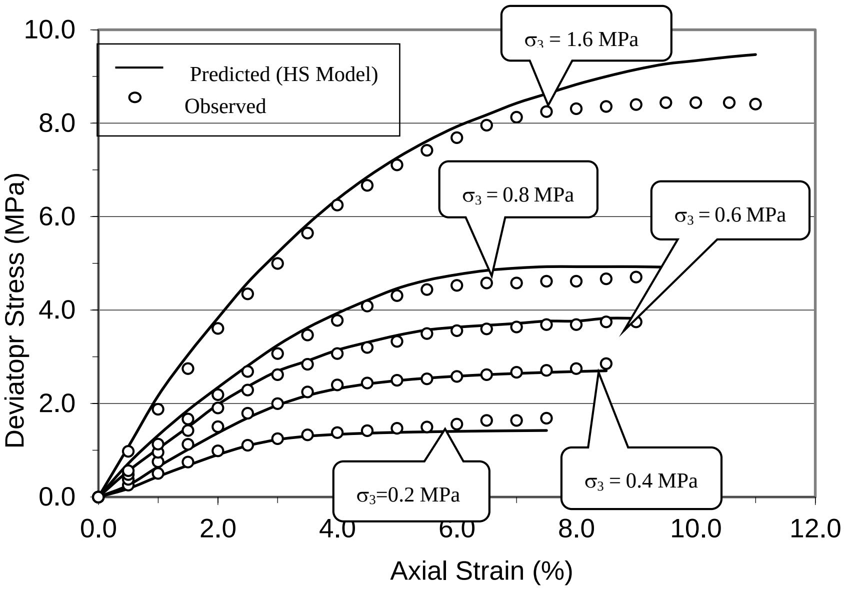
(a) Stress-Strain Behaviour



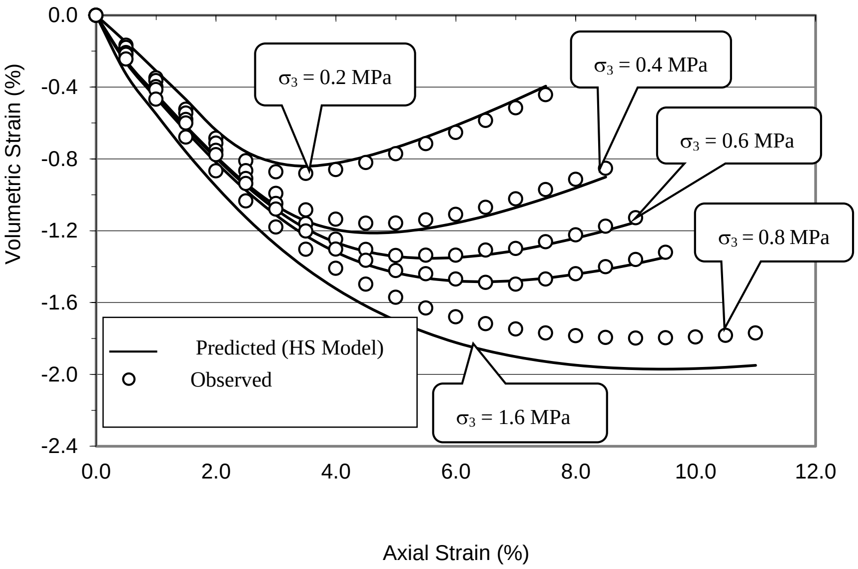
(b) Volume Change Behaviour

Figure 3: Observed and Predicted Stress-Strain-Volume Change Behaviour of Mod

eled Alluvial Rockfill Material (d_{max} = 4.75 mm) tested for 87% Relative Density



(a) Stress-Strain Behaviour



(b) Volume Change Behaviour

Figure 4: Observed and Predicted Stress-Strain-Volume Change Behaviour of Mod eled Quarried Rockfill Material (d_{max} = 4.75 mm) tested for 87% Relative Density

Table 2: ϕ-Values of the Alluvial and Quarried Rockfill Materials

Rockfill Materials from	RD (%)	ϕ -Value (degree)					
		4.75 mm	10 mm	19 mm	25 mm	50 mm	80 mm
Alluvial	87	36.3	38.6	39.9	40.8	42.5	43.9
	75	34.5	36.8	38.2	39.4	41.5	42.8
Quarried	87	47.5	46.8	46.0	45.1	44.2	43.1
	75	46.2	45.1	43.8	42.7	41.1	39.7

3.3 Predictions:

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 [2].

In the second phase the 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 [2].

Using elastic, shear strength and other material strength parameters required for HS model and following the above procedure, the stress-strain-volume change behaviour was predicted and compared with the experimental results for all the d_{max} of both modeled rockfill materials considered in the present study. Material parameters determined for alluvial and quarried [2]. Typical experimental and predicted stress-strain-volume change behavior for both rockfill materials tested on d_{max} of 4.75 mm with 87% RD are shown in Figs. 3 and 4 respectively. Comparing experimental and predicted stress-strain-volume change behavior, it is observed that the results match closely for both rockfill materials. Therefore, the elasto-plastic HS constitutive model can be used successfully for characterizing the behavior of rockfill materials.

3.4 Prediction of Material Parameters for Prototype Rockfill Material

3.4.1 Strength Parameters: The following strength law proposed by [9] has been used in this research work for the rockfill materials:

$$\frac{\sigma_1 - \sigma_3}{P_a} = B'\left[\frac{\sigma_1 + 2\sigma_3}{P_a}\right]^{\alpha'} \quad (1)$$

where, B' is a non-dimensional parameter based on material characteristics of the rockfill material and α' is non-dimensional parameter dependent on principal stresses at failure [2].

The parameter B' has been related with the basic characteristics of rockfill materials viz. UCS, UVC and RD. In the present paper, the relationship of B' with basic characteristics of the rockfill material has been proposed as

$$B' = C(P)^{p_1}(UVC)^{p_2}(RD)^{p_3} \quad (2)$$

where, C is the coefficient and p_1, p_2 and p_3 are exponents. P is defined as UCS/UCS_{max} i.e. the ratio of UCS of the material to the maximum UCS among all the tested alluvial and quarried rockfill materials considered separately in the analysis for developing the procedures [2]. UVC value determined for all d_{max} of alluvial and quarried rockfill material is expressed as a fraction. The RD is also expressed as a fraction i.e. 0.87 and 0.75 in the present case.

Based on experimental values of σ_1 for different σ_3, the average value of B′ for each modeled d_{max} of all the above riverbed and quarried rockfill materials has been determined using Eq. (2). From the known values of P, UVC, RD and B′ for each modeled d_{max} of all the alluvial and quarried rockfill materials, C, p_1, p_2 and p_3 are determined. A FORTRAN computer programme has been developed and used to find out C and p_1, p_2 and p_3 separately for riverbed and quarried rockfill materials using least squares fitting method. Then, the Eq. (2) becomes as

for riverbed rockfill materials

$$B' = 0.995(P)^{0.218}(UVC)^{0.164}(RD)^{0.351} \quad (3)$$

for quarried rockfill materials,

$$B' = 1.499(P)^{-0.062}(UVC)^{0.620}(RD)^{-0.085} \quad (4)$$

Using Eqs. 3 and 4, by substituting the values of P, UVC and RD to the corresponding $d_{max,}$ the B' can be determined for alluvial and quarried prototype rockfill materials. Then the prototype material strength parameters (dilatancy angle, ψ and initial void ratio, e_{init}) required for HS model have been determined by correlating with B′ value of rockfill materials as B′ is a function of the basic characteristics of the rockfill material using a best fit linear extrapolation for both rockfill materials.

3.4.2 Elastic Parameters: The elastic material parameters required for hardening soil (HS) model viz. E_{50}^{ref}, E_{oed}^{ref}, E_{ur}^{ref} and ν have been determined from the laboratory test results for all the alluvial and quarried modeled rockfill materials. The reference stiffness modulus, E_{50}^{ref} has been correlated with index property of rockfill material, UVC, confining pressure, σ_3 and modulus of elasticity of intact rock, E_{ir} as

$$\frac{E_{50}^{ref}}{E_{ir}} = C(UVC)^{T_1}\left(\frac{\sigma_3}{P_a}\right)^{T_2} \quad (5)$$

where, T_1 and T_2 are the exponents, E_{ir} is the modulus of elasticity of intact rock from which rockfill materials are derived and C is the coefficient. Similarly, the Poisson's ratio, ν is proposed to be correlated with index property of rockfill material, UVC, σ_3 and Poisson's ratio of intact rock, ν_{ir} as

$$\frac{\nu}{\nu_{ir}} = D(UVC)^{T_3}\left[\frac{\sigma_3}{P_a}\right]^{T_4} \quad (6)$$

where, T_3 and T_4 are the exponents, ν_{ir} is the Poisson's ratio of intact rock from which rockfill materials are derived and D is the coefficient. The values of E_{ir} and ν_{ir} are obtained by following the ISRM suggested method [5].

Using a developed computer programme and following the procedure explained earlier, C, D and T_1, T_2, T_3 and T_4 were determined separately for alluvial and quarried rockfill materials using least squares fitting method. Then the elastic parameters of rockfill materials are given by for alluvial rockfill materials,

$$\frac{E_{50}^{ref}}{E_{ir}} = 2.225x10^{-4}\left(UVC\right)^{-0.878}\left(\frac{\sigma_3}{P_a}\right)^{0.326} \quad (7)$$

$$\frac{\nu}{\nu_{ir}} = 2.04(UVC)^{0.615}\left[\frac{\sigma_3}{P_a}\right]^{-0.031} \quad (8)$$

for quarried rockfill materials,

$$\frac{E_{50}^{ref}}{E_{ir}} = 3.038x10^{-3}\left(UVC\right)^{1.697}\left(\frac{\sigma_3}{P_a}\right)^{0.512} \quad (9)$$

$$\frac{\nu}{\nu_{ir}} = 1.173(UVC)^{0.085}\left[\frac{\sigma_3}{P_a}\right]^{-0.045} \quad (10)$$

Substituting the values of E_{ir}, UVC and σ_3 to the corresponding d_{max} of alluvial and quarried prototype rockfill material, the value of E_{50}^{ref} has been determined. Similarly, the Poisson's ratio is determined for both projects prototype rockfill materials. The elastic and material strength parameters of both prototype rockfill materials (with d_{max}=600 mm) required for HS model are determined [2]. Using the elastic and material strength parameters of both prototype rockfill materials, stress-strain-volume change behavior was predicted using HS model [2]. The predicted behavior of prototype rockfill material, in general, follows similar trend as modeled rockfill materials. Therefore, the predictions appear to be satisfactory [2]

4. Conclusions

The basic index properties, viz. UCS and UVC of modeled rockfill materials for alluvial and quarried were determined. Drained triaxial tests have been conducted on all the d_{max} of both rockfill material with σ_3 varying from 0.2 to 1.6 MPa at RD of 87% and 75%. The HS constitutive model based on elasto-plastic theory has been adopted to characterize stress-strain-volume change behavior of modeled and prototype rockfill materials.

Based on the laboratory test results, the elastic (E_{50}^{ref}, E_{oed}^{ref}, E_{ur}^{ref} and ν) and material strength parameters (ϕ, ψ, c, m') of modeled rockfill materials were determined for both projects rockfill materials. Procedures have been proposed to predict the elastic and shear strength parameter of modeled rockfill materials. Comparing predicted and experimentally determined elastic and shear strength parameters, it is observed that both results match closely. Using the predicted material parameters, stress-strain-volume change behaviour was back predicted for modeled rockfill material using HS model and compared with the observed behaviour. From the comparison, it is observed that both predicted and observed beahviour match closely. Therefore, these procedures have been used to predict the elastic, shear strength and material strength parameters for large size prototype rockfill materials. The material strength parameters of prototype rockfill materials required for HS model were determined by correlating material strength parameters of prototype rockfill materials with B′ value as B′ is a function of the basic characteristics of the rockfill material. Material strength parameters for prototype rockfill materials were determined using a best fit linear extrapolation with respect to B′. Using these material parameters, stress-strain-volume change behavior of prototype rockfill materials were predicted using HS model. The predicted behavior of prototype rockfill materials, in general, follows similar trend as modeled rockfill materials. Therefore, the predictions made by HS model appear to be satisfactory.

The advantage of the proposed methods is that only index properties viz. UCS, UVC, RD, modulus of elasticity of intact rock, E_{ir} and Poisson's ratio of intact rock, ν_{ir} are required to be obtained to determine ϕ-value, modulus of elasticity, E_{50}^{ref} and Poisson's ratio, ν of rockfill materials and there is no need of triaxial testing. It is believed that the proposed methods are more realistic, economical, and can be used where large size triaxial testing facilities are not available.

5. Acknowledgement

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