Interpretation of stress-dependent mechanical behaviour of rockfill materials

Interprétation de stress-dépendante et comportement mécanique de matériaux enrochement

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ABSTRACT: This paper studies thoroughly the mechanical behavior of thirty types of rockfill materials subjected to triaxial compression shearing, each with three different confining stresses. The materials' characteristics, including mineralogy, gradations and shape of particles; and also the tests' results have been collected from the literature. The Hyperbolic Model (Duncan and Chang 1970) is employed as a framework for interpreting the mechanical behavior of the materials. Features of the behavior of the rockfill materials, as compared with that of soils, are highlighted through the exponent parameter (n) of the Hyperbolic Model. It is shown that unlike for soils, the exponent number, n, is not constant for a given rockfill material, and that the n value depends on the confining stress level; for the materials under high pressures, n can even takes a negative value, which is a sign of particle breakage of the materials. Two correlations for estimating initial elasticity modulus (E_i) and internal friction angle (φ) of these materials are suggested.

RÉSUMÉ : Cet article étudie soigneusement le comportement mécanique de trente types de matériaux enrochement soumis à un cisaillement triaxial chacun avec trois différentes contraintes de confinement. Les caractéristiques du matériau : minéralogie, gradations et forme des particules et aussi les résultats du test ont été collectés à partir de la littérature. Le modèle hyperbolique (Duncan et Chang 1970) est utilisé en tant que cadre pour l'interprétation du comportement mécanique des matériaux. Les caractéristiques du comportement des matériaux en enrochement, par rapport à celles des sols, sont mises en évidence par le paramètre d'exposant (n) du modèle hyperbolique. Il est montré que, contrairement aux sols, le nombre d'exposants, n, n'est pas constant pour un matériau donné en enrochement et, en ce que la valeur de n dépend du niveau de contrainte de confinement ; pour les matériaux à hautes pressions, n peut même prendre une valeur négative, ce qui est un signe de rupture des particules de matières. Deux corrélations pour estimer le module d'élasticité initial (E_i) et l'angle (φ) de frottement interne de ces matériaux sont proposées.

KEYWORDS: Rockfill Materials, Triaxial Compression Shearing, Hyperbolic Model, Initial Elasticity Modulus.

1 INTRODUCTION

Shear strength and deformation characteristics of rockfill materials depend generally on different parameters, such as mineralogy, grain size distribution, size of particles, stress level, and particle breakage (if any). The importance of particle breakage goes back to its capability of changing gradations of granular materials.

This paper presents the results of a comprehensive study on the mechanical behaviour of thirty rockfill materials under medium and large scale triaxial testing. Data about the materials and the tests are gathered from the literature. The Hyperbolic Model (HM) is employed as an analytical and behavioural framework for this study. The important parameters of the HM for the rockfill materials are determined and compared with similar parameters for typical loose and dense sands. Variations of deformation and strength parameters (E_i and φ) of the materials with confining stress (σ_3) are studied. On the basis of this study, two relationships for estimating E_i and φ of the rockfill materials are proposed.

2 PROPERTIES OF ROCKFILL MATERIALS

Thirty types of rockfill materials, on which conventional triaxial compression tests had been carried out, are used in this study. The material characteristics, including mineralogy, uniformity coefficient, shapes of particles and etc. for three types of these materials are presented in Table 1. Because of conciseness the presenting of the all of materials characteristics has been neglected.

3 HYPERBOLIC MODEL AND ITS APPLICATION

3.1. *Theory of the model*

The Hyperbolic Model (Duncan & Chang 1970) considers the behavior of a soil specimen under compressive triaxial testing as a hyperbola. According to the model, the gradient of the tangent to the stress-strain relationship (q:ε_a), namely as tangential deformation modulus (E_t), is defined as follows:

$$E_t = \left\{1 - \frac{R_f(1-\sin\varphi)(\sigma_1-\sigma_3)}{2C\ \cos\varphi + 2\sigma_3 \sin\varphi}\right\}^2 KP_a \left(\frac{\sigma_3}{P_a}\right)^n \tag{1}$$

Where φ= internal friction angle; C= cohesion; K= modulus number; n= exponent number, R_f= failure ratio; and P_a= atmospheric pressure.

The above parameters for a given material can be obtained by carrying out, usually, three triaxial tests on the soil's specimens.

Parameters K, n, and R_f are usually determined from the triaxial tests results and on the basis of a nonlinear stress- strain behavior, which is assumed as a hyperbola (Konder 1963). The Hyperbola equation is as follows:

$$\frac{\varepsilon_a}{(\sigma_1-\sigma_3)} = a + b\varepsilon_a \tag{2}$$

Where σ_1= maximum principal stress; σ_3= minimum principal stress; and ε_a= axial strain in triaxial compressive testing. Parameters a and b=the reverses of initial elasticity modulus (E_i) and ultimate deviatoric stress $(\sigma_1-\sigma_3)_{ult}$, respectively. These parameters can be determined by drawing a fitting line to the tests results, as shown in Figure 1. R_f is defined as follows:

$$R_f = \frac{(\sigma_1-\sigma_3)_f}{(\sigma_1-\sigma_3)_{ult}} \leq 1.0 \tag{3}$$

Where $(\sigma_1-\sigma_3)_f$ = the deviatoric stress at failure.

The following relationship for the initial modulus of elasticity for soils is suggested (Janbu 1963):

$$E_i = kP_a\left(\frac{\sigma_3}{P_a}\right)^n \tag{4}$$

Where, n represents the exponential effect of σ_3 on E_i. K and n can be determined by drawing a line fitted to data of the triaxial tests, as presented in Figure 2.

Table 1. Mechanical properties of three rockfill materials

Rockfill Type	Australia Railway Ballast	Roodbar Dam Material	Yamchi Dam Material
Mineralogy	Latite basalt	Lime stone	Andesite
D_{min}(mm)	20	0.15	0.072
D_{max}(mm)	65	50.8	74.3
C_u	1.5	23	65.4
σ_3(kPa)	90 120 240	500 700 900	200 400 700
φ°	54.6 52 45.8	30.6	38.7
B_g^* (%)	10	11 12 13.5	NIA**
Shape	Highly Angular	Angular/ sub Angular	Rounded

*** NIA: No Information Available*

** B_g : Marsal's breakage index*

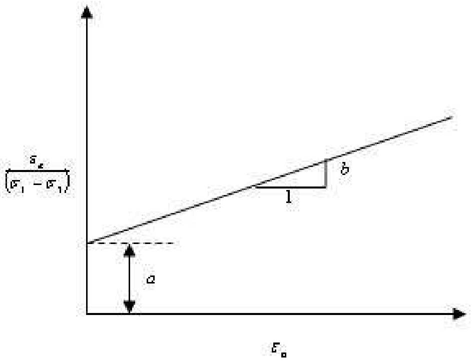

Figure 1. Determining constants a and b from a triaxial test results

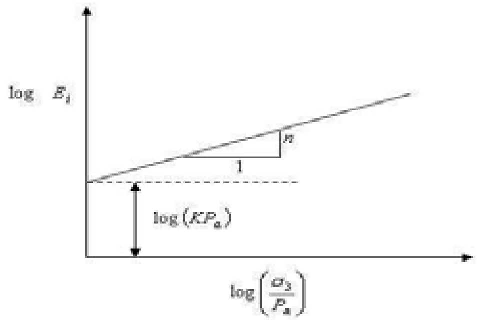

Figure 2. Determining constants n and K from three triaxial tests results

3.2. *Application of the model*

In this section, the mechanical behavior of the thirty rockfill materials, which the characteristics of three types of them are presented in Table 1, are investigated analytically in the framework of the Hyperbolic Model. Values of parameters n and K for the materials introduced in Table 1, for every two consecutive triaxial tests, and furthermore, for three triaxial tests, are extracted and presented in Table 2. Therefore, for each of the materials three values of n are calculated; one from the first and second triaxial tests results, one from the second and third triaxial tests results, and one from first, second and third triaxial tests. We intentionally calculated the first two values for n to highlight the effect of particle breakage on E_i (through n) with every increase of σ_3. This is different from the similar procedure of determining n for soils, where usually a unique n value can be extracted from results of triaxial tests with three consecutive confining stresses (σ_3) on a given material. The details of determining n and K from the triaxial tests results are given in Duncan and Chang 1970.

Table 2. Values of n and K parameters for the rockfill materials introduced in Table 1

Rockfill Type	$(\sigma_3)_1$, $(\sigma_3)_2$ (kPa)	n	K
Australia Railway Ballast	90, 120	-7.45	3500
	120, 240	-0.95	1070
	90,120 ,240	-3.32	2100
Roodbar Dam Material	500, 700	-6.53	18×10^8
	700, 900	-1.15	52000
	500,700, 900	-3.26	10×10^5
Yamchi Dam Material	200, 400	2.7	1180
	400 , 700	0	5×10^4
	200,400, 700	1.5	3000

Table 3 compares the average values of n for the relatively rounded and relatively angular rockfill materials of this study separately, with typical values for loose and dense sands. As expected, the average n for the rockfill materials are far less than that of the typical dense sand; moreover, n reduces with increasing of the materials' angularity. It should be mentioned that highly angular, angular, angular/sub angular and sub angular materials are assumed as relatively angular materials; while, rounded, rounded/sub rounded and sub rounded ones are assumed as relatively rounded materials.

Table 3. Average values of n and K for relatively rounded and relatively angular rockfill materials, compared with typical values for loose and dense sands

Type of Materials	Relatively Angular	Relatively Rounded	Loose Sand	Dense Sand
n	0.085	0.29	0.65	0.54
K	2004	700	300	2000

The main factor responsible for the comparatively lower (compared with sands) average values of n for the rockfill materials (especially the angular ones) is particles breakage which happens during both compression and shearing of the materials.

According to Eq. 4, n represents the exponential effect of σ_3 on E_i. As particle breakage in rockfill materials is far more than in sands, the average n value of rockfill materials is much less than that of sands. Materials with higher degrees of angularity suffer more particle breakage and therefore, they have lower values of n.

The modulus number (K in Eq. 4) for the studied rockfill materials takes values ranging widely from 53 to 36×10^9. The very high values of K correspond to negative values of n.

4 VARIATION OF E_i AND φ WITH CONFINING PRESSURES (σ_3)

Figure 3 shows the variations of E_i with σ_3 while shown in Figure 4 is the variations of φ with σ_3 for one of the highly angular and one of the rounded materials which are studied in this paper. As Figure 3 shows, because of massive particle breakage, the increasing of σ_3 has resulted in the reduction of E_i for the highly angular rockfill material, while E_i has increased with a gentle slope with the increase of σ_3 for the rounded rockfill material. Moreover, the rate of reduction of φ with the increase of confining pressure is much more for the highly angular material than for the rounded material, as presented in Figure 4.

The above trends of variations were obvious more or less in the behavior of the rest of the materials. Our studies on the behavior of the materials showed that the following factors have major effects on the rate of particle breakage:

- Shape of particles: angular particles undergo more breakage.
- Mineralogy: particles of weaker materials break more.
- Size of particles: coarse particles are more vulnerable to breakage.
- Coefficient of Uniformity (C_u): A lower C_u, causes a higher rate of particle breakage.

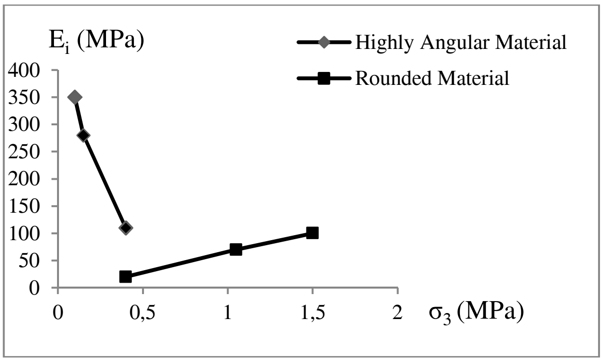

Figure 3. Variations of E_i with σ_3 for typical rounded and highly angular rockfill materials

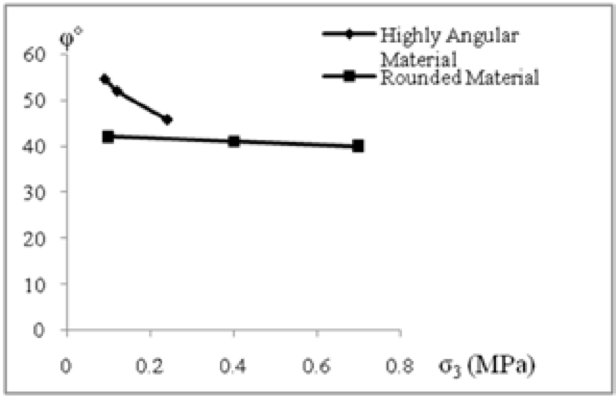

Figure 4. Variations of φ with σ_3 for typical rounded and highly angular rockfill materials

It should be mentioned that according to Equation 4, the particle breakage phenomenon affects the tangential deformation modulus (E_t) of rockfill materials by both "n" and "φ ".

The above conclusions strongly suggest that the variations of deformation modulus of rockfill materials with confining pressure should be taken into account in deformation analyses of rockfill structures.

5 CORRELATION BETWEEN E_i AND φ WITH σ_3

This study on the triaxial testing results of the rockfill materials led to two correlations between E_i and φ with σ_3. They are as follows:

$$\frac{\Delta\varphi}{\varphi_0} = -\alpha\ \log\left(1+\frac{\Delta\sigma_3}{\sigma_{3_0}}\right) \tag{5}$$

where Δφ = reduction of internal friction angle; φ_0 = internal friction angle corresponding to σ_{30}; σ_{30}= initial confining stress, which is usually the minimum confining stress in triaxial testing; $\Delta\sigma_3$= confining pressure increase; and α= a coefficient depending on shape of particles, coefficient of uniformity (C_u), and confining pressure increment ratio ($\Delta\sigma_3/\sigma_{30}$).

Considering the studied rockfill materials, α ranges between 0.051 and 0.59 for the relatively angular materials and between 0.046 and 0.42 for the relatively rounded materials.

It implies that α for the rounded materials are generally less than that for the angular ones; this represents the lower particle breakage potential for the rounded materials.

The relationship for variation of E_i with σ_3 is suggested, as follows:

$$\frac{\Delta E_i}{E_{i_0}} = \beta\left(\frac{\Delta\sigma_3}{\sigma_{3_0}}\right) \tag{6}$$

where ΔE_i= changes in initial elasticity modulus; E_{i0}=initial elasticity modulus corresponding to σ_{30}; and β= a coefficient depending on particle shapes, uniformity coefficient (C_u), and $\Delta\sigma_3/\sigma_{30}$ in triaxial compression shearing.

For the relatively angular materials, β was calculated as $-2.65 \leq \beta \leq 3.71$ and for the relatively rounded materials as $-1.14 \leq \beta \leq 5.50$. It is observed that the range of positive values of β, which implies the increase of E_i with σ_3 , for the relatively angular materials are smaller than the similar range for the rounded materials (3.71 versus 5.50). For the range of negative values of β, which implies the decrease of E_i with σ_3, the trend is opposite (-2.65 versus -1.14). The above observation is logical concerning comparatively higher particle breakage and its reductive effect on E_i in the relatively angular materials.

6 CONCLUSIONS

This paper studied thoroughly the mechanical behavior of thirty rockfill materials subjected to triaxial compression shearing with three different confining stresses. The Hyperbolic Model (Duncan and Chang 1970) was employed as the behavioral model for this study. Features of the mechanical behavior of rockfill materials, as compared with soils, were highlighted through the exponent parameter (n) of the Hyperbolic Model. Unlike for soils, n is not constant for rockfill materials, and depends on confining stress levels; n can even takes a negative value, which is a sign of particle breakage in the materials.

The main focus in this paper was on the effect of confining pressure on the stiffness (initial deformation modulus and tangential deformation modulus) of the materials. It was shown that rockfill materials undergo particle breakage to some extents and therefore, they may behave comparatively softer under higher confining stresses. The extent of particle breakage depends on gradation characteristics, (especially coefficient of uniformity), particle shape (angular or rounded), wetting condition, and confining stress.

Two correlations for estimating initial elasticity modulus (E_i) and internal friction angle (φ) of the studied rockfill materials, based on particles shape, confining pressure (σ_3), and coefficient of uniformity (C_u) were suggested. Investigations on the variations of internal friction angle (φ) with confining stress (σ_3) also showed that φ decreases with increasing of σ_3 in all types of rockfill materials. The extent of reduction in φ depends on the extent of particle breakage.

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