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To cite this article: Katarzyna Dolzyk-Szypcio 2019 *IOP Conf. Ser.: Earth Environ. Sci.* **221** 012013

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Stress-Dilatancy of Rounded and Angular Rockfill Materials

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Abstract. Rockfill materials consist primarily of angular to subangular particles obtained by blasting rock or extracting rounded to sub rounded particles from river bed. The stress-strain (stress-dilatancy) behaviour of rockfill materials is affected by mineralogical composition, particle grading, size and shape of particles and stress level. Particle breakage has an important effect on strength and stress-dilatancy behaviour. Based on a large scale triaxial tests data reported in literature, the stress-dilatancy relationship is analysed using *Frictional State Theory*. It is shown that stress level significantly influences the stress-dilatancy relationship. The double-effect of particle breakage may be observed: one – the energy consumed for breakage during shear, and the other – the extra contraction caused by breakage. Parameter α of *Frictional State Theory* represents the energy consumption effect and β represents extra contraction caused by breakage. It is shown that *Frictional State Theory* can reflect the influence of particle breakage on stress-strain behaviour of rockfill material.

1. Introduction

Inherent flexibility, capacity to absorb large seismic energy, adaptability to various foundation conditions and using local available materials make rockfill dams an optional solution [1,2]. Rockfill may be defined as a coarse grained and free draining material obtained by blasting rock or extracting from river beds. The rockfill obtained by blasting consists primarily of angular to subangular particles and the one extracted from river bed - of rounded to sub rounded particles [1, 3, 4, 5]. It is expected that rockfill with angular particles behaves similarly to rail ballast [6,7] and with rounded particles – similarly to gravel [8]. The coarseness of the particles and their interlocked state makes it very difficult to sample and laboratory tests as for other soils. The large and moderately large equipment has to be used for test [2]. The laboratory test specimen may be scaled down to some degree as well as being reconstituted by compaction [1, 9, 10, 11, 12]. Particle breakage has a significant influence on the stress-strain and strength of rockfill material and makes modelling very difficult [13, 14, 15]. Generally, models have large number parameters which are difficult to mark in conventional laboratory tests [16]. It is known that Modified Cambridge model and Rowe's relation cannot reflect the dilatancy behaviour of coarse materials, especially rockfill. The three parameters of *Frictional State Theory* (Φ° , α , β) give possibilities to describe the influence of stress level (breakage) on stress-dilatancy relationship of rockfill.

The critical frictional state angle Φ° value is independent of stress level. The breakage causes two effects: one which is energy consumption for particle breakage represented by parameter α , and the other extra contraction during shear represented by parameter β .

The present paper analyses the stress-dilatancy relationship of rockfill tested in triaxial compression at different confining pressure and two initial relative densities (Li et al. [15]). It is shown



that stress level and initial density influence the stress-dilatancy relations and may be quantified using *Frictional State Theory*.

2. Stress-dilatancy for drained triaxial compression

Based on *Frictional State Theory*, the stress-dilatancy relationship for drained triaxial compression has the following form [17, 18]:

$$\eta = Q - AD^P \quad (1)$$

where

$$q = \sigma'_1 - \sigma'_3 \quad (2)$$

$$p' = \frac{1}{3}(\sigma'_1 + 2\sigma'_3) \quad (3)$$

$$Q = M_c^o - \alpha A_c^o \quad (4)$$

$$A = \beta A_c^o \quad (5)$$

$$D^P = \delta \varepsilon_v^P / \delta \varepsilon_q^P \quad (6)$$

$$\delta \varepsilon_v^P = \delta \varepsilon_1^P + 2\delta \varepsilon_3^P \quad (7)$$

$$\delta \varepsilon_q^P = \frac{2}{3}(\delta \varepsilon_1^P - \delta \varepsilon_3^P) \quad (8)$$

$$\delta \varepsilon_v^P = \delta \varepsilon_v^e - \delta \varepsilon_v^e \quad (9)$$

$$\delta \varepsilon_q^P = \delta \varepsilon_q^e - \delta \varepsilon_q^e \quad (10)$$

$$\delta \varepsilon_v^e = \frac{\delta p'}{K} \quad (11)$$

$$\delta \varepsilon_q^P = \frac{\delta q}{3G} \quad (12)$$

$$K = \frac{2}{3} \frac{1+\nu}{1-2\nu} G \quad (13)$$

for sands and rockfill [15]

$$G = G_o \frac{(2.973 - e)^2}{(1 + e)} \sqrt{p' p_a} \quad (14)$$

where Φ° is the angle of critical frictional state, α and β are *Frictional State Theory* parameters. The G_o - material constant, p_a - atmospheric pressure, e - void ratio, ν -Poisson's ratio.

The parameters of analysed rockfill materials taken for calculation are summarized in Table 1.

Generally, in modelling of soils, ν is taken as constant (independent of stress level). In this paper, stress-dilatancy relationship for values ν independent of stress level is incorrect.

The analysed rockfill consists of coarse angular and subangular particles easier to break than sand.

Table 1. Elastic parameters of rockfill.

Relative density	Confining pressure	G_o	ν
[-]	[kPa]	[-]	[-]
0.60	300	190	0.35
	600		0.20
	1000		0.10
0.90	300	190	0.30
	600		0.20
	1000		0.15

3. Shear behaviour of rockfill

The behaviour of rockfill during drained triaxial compression tests conducted by Li et al. [15] is analysed. The sample of rockfill with two relative densities were sheared at confining pressure 300, 600 and 1000 kPa. The relationships: $\sigma_1'/\sigma_3' - \varepsilon_a$ and $\varepsilon_v - \varepsilon_a$ are shown in Figures 1 and 2.

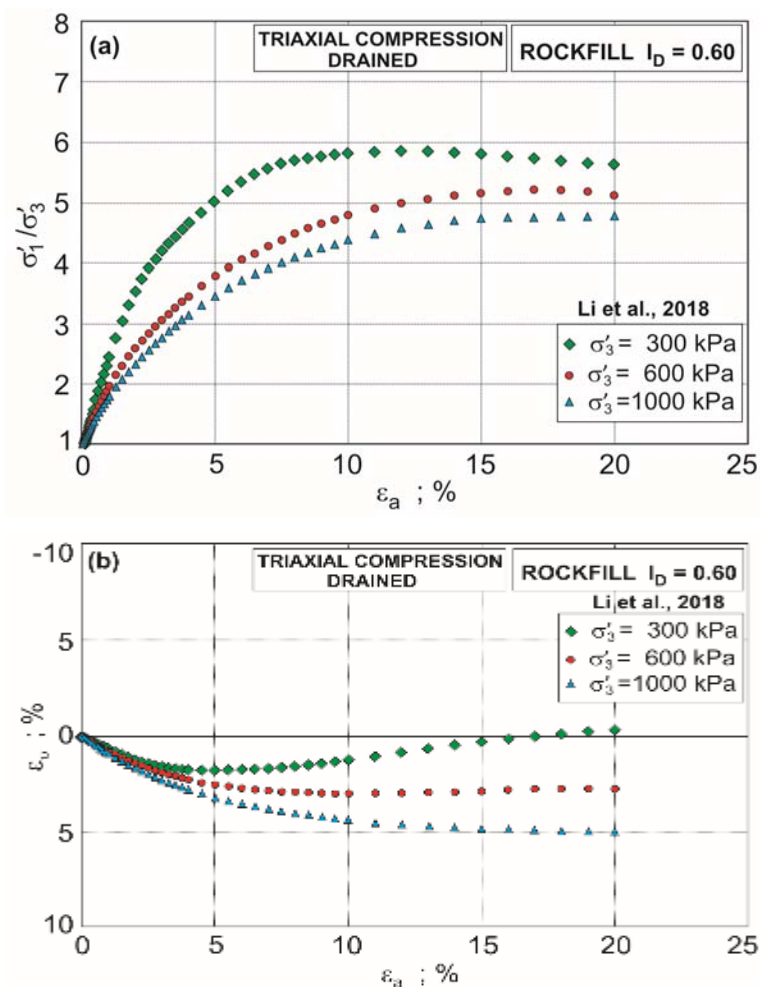


Figure 1. Triaxial tests results for rockfill with relative density 0.60:
a) $\sigma_1'/\sigma_3' - \varepsilon_a$; b) $\varepsilon_v - \varepsilon_a$ (based on [15])

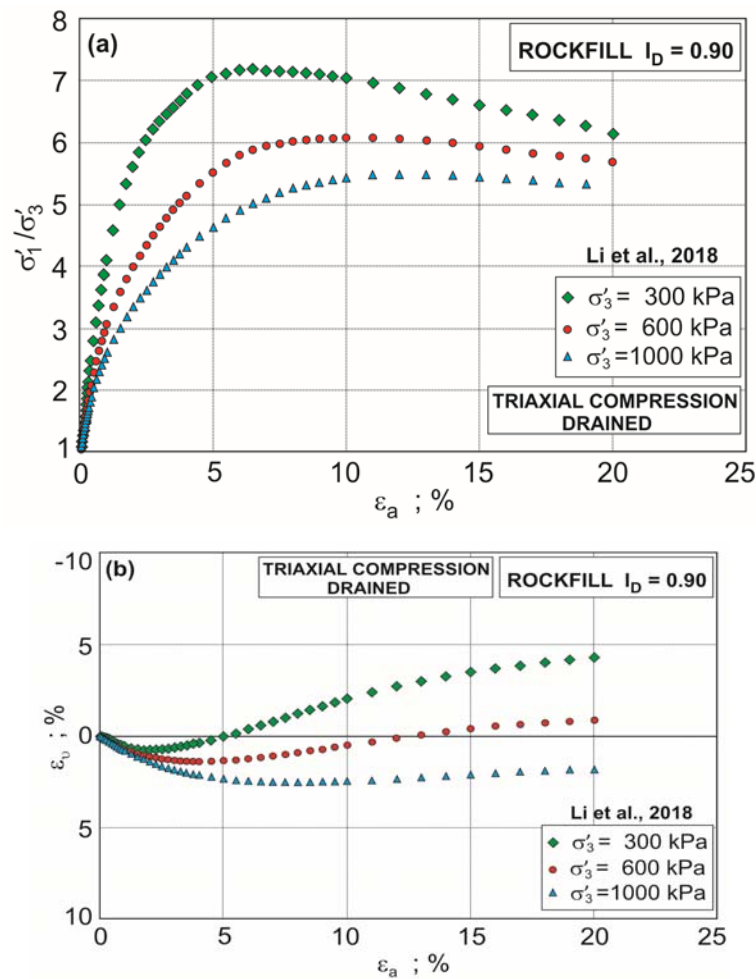


Figure 2. Triaxial tests results for rockfill with relative density 0.90:

a) σ'_1/σ'_3 - ε_a ; b) ε_v - ε_a (based on [15])

The stress-dilatancy relationships were calculated by sectional approximation changes of main stress ratio (σ'_1/σ'_3) and volume strain ε_v by high degree polynomials. Calculations were done with the use of elastic parameters shown in Table 1. The obtained stress-dilatancy relationships are shown in Figures 3 and 4.

In Figures 3 and 4 *Frictional State Lines* representing equation (1) for $\alpha=0$ and $\beta=1$ [18] are also shown. It is visible that all three stress-dilatancy lines for relative density 0.60 are crossing vertical axle at $\eta=1.685$ so $\Phi^\circ=41.1^\circ$. The stress-dilatancy lines for $\sigma_3=300$ and 1000 kPa are almost identical except for the initial phase of shearing, where elasticity strains are significant.

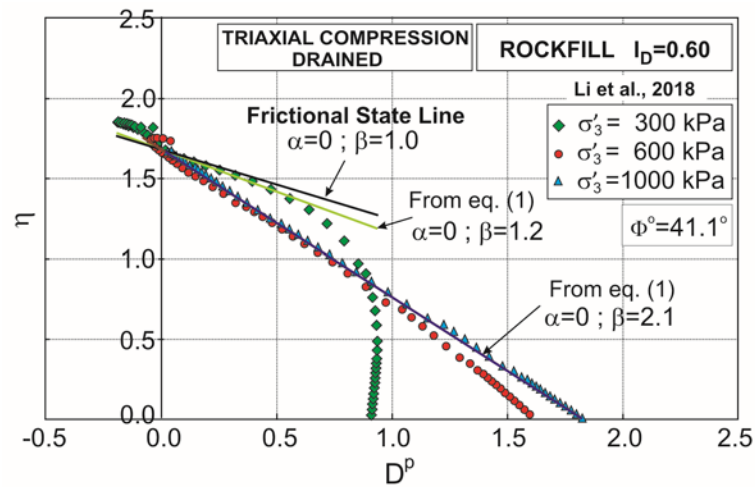


Figure 3. Stress-dilatancy relationship for rockfill with relative density 0,60

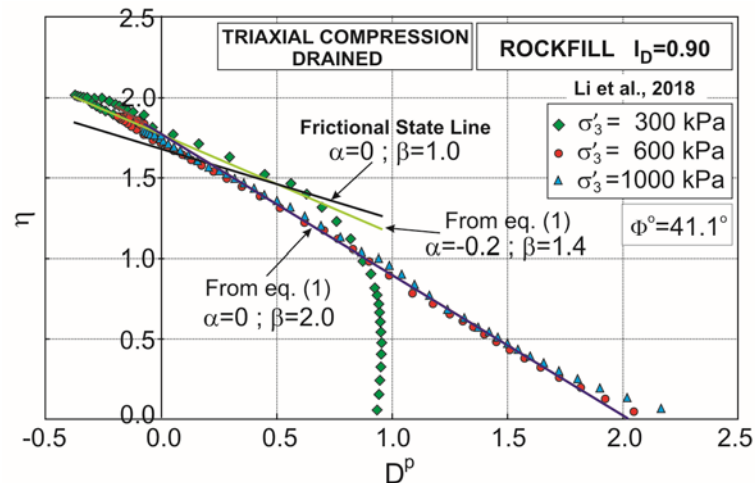


Figure 4. Stress-dilatancy relationship for rockfill with relative density 0,90

Good approximations of experimental stress-dilatancy relationships represented by equation (1) were obtained for parameters α and β shown in Table 2.

Table 2. Parameters: Φ° , α , and β

Relative density [-]	Confining pressure [kPa]	Φ° [°]	α [-]	β [-]
0.60	300	41.1	0.00	1.20
	600		0.00	2.10
	1000		0.00	2.10
0.90	300	41.1	-0.20	1.40
	600		-0.20	2.00
	1000		-0.20	2.00

Parameter α represents the influence of energy consumption on breakage while $(\beta-1)$ influence of extra contraction caused by breakage on stress-dilatancy relationship.

For relative density 0.60 energy consumed for breakage is negligibly small, but for relative density 0.90 it is noticeable. Unexpectedly, for both relative densities values β are similar for the same confining pressures. It means that the influence of extra volume contraction caused by breakage has similar effect for both relative densities. The behaviour of analysed rockfill is similar to latite basalt and railway ballast [6, 7]. Contrary to that, gravel with coarse rounded particles does not exhibit the influence of breakage on stress-dilatancy relationship [8] at a similar stress level. Therefore, the shape of coarse particles affects stress-dilatancy relationship.

4. Conclusions

Frictional State Theory gives an opportunity to simply describe stress-dilatancy of soils and also shows breakage during shear.

Parameters α and β can separately quantify the influence of energy consumption for particle breakage and extra contraction caused by breakage on stress-strain behaviour.

The application of *Frictional State Theory* can make it possible to reduce the number of parameters in soil modelling in the future.

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