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Testing of Rockfill Materials: A Review

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Abstract. Rockfill dams are getting popular because of flexibility in nature, ability to absorb large seismic energy and suitability to any foundation conditions. Rockfill material is being used as a natural construction material for different types of civil structures like dams, embankments, Roads, slope protection, costal protection, dykes etc. Modern heavy earthmoving equipments and locally available rockfill material make the structures and economical too.

In the present paper, research and development of Rockfill material (RFM) has been reviewed and presented. Large size triaxial test results obtained from the tests carried out in Central Soil & Materials Research Station (CSMRS), New Delhi have been compared with the results of works carried out by other researches for different types of RFM. The effect of maximum particle size (d_{max}), confining pressure (σ_3), dilatancy angle (Ψ) and particle breakage (Bg) and angle of shearing resistance (ϕ) have been studied and presented. From the research and development study carried out, it is concluded that the shear strength of RFM greatly depends on $d_{max,}$ $\sigma_{3,}$ Bg, Ψ and gradation of material.

Keywords: Rockfill; particle breakage; dilatancy.

1 Introduction

Number of river valley projects are being planned and implemented in India and abroad to store the natural water flowing in the rivers and use it later for different purposes viz. power generation, irrigation and flood control etc. Concrete, Masonry and Earth and rockfill dams are being constructed to store the river water. However, now a days, rockfill dams are widely being constructed all over the world because of their inherent flexibility, capacity to absorb large seismic energy, adaptability to various foundation conditions and economical as well. The behaviour of the rockfill materials used in the earth and rockfill dam is of considerable importance for the analysis, safe and economical design of rockfill dams. The prototype rockfill material used in the dam construction is large in size and it is not feasible to test it directly in the laboratory. Therefore, 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 prepared and tested in the laboratory. Among all available modeling techniques, the parallel gradation technique (Lowe 1964) is most commonly used and the same has been adopted in the present study. The behaviour of the rockfill materials has been reported by number of researchers, Marsal [20, 21], Mirachi et al. [18,19], Gupta [3,4,5], Honkanadavar [6,7,8 & 9] and Varadarajan et al. [22,23 & 24]. Honkanadavar [6,7,8 & 9] have performed laboratory tests on various rockfill materials with different confining pressures in CSMRS. They concluded that the strength parameter varies with the particle size. They had also observed that the trend of behaviour of alluvial rockfill material is opposite to that of blasted quarried rockfill material. For blasted quarried rockfill materials the angle of internal friction, ϕdecreases with increase in d_{max} and for alluvial rockfill material the angle of internal friction. ϕincreases with increase in d_{max}

The main objective of this paper is to study the research & development works carried out by CSMRS and the works carried out by other researchers. This paper summarizes the tests data reported by CSMRS's scientist Honkanadavar [6, 7, 8, 9 & 10], and other authors Indraratna [11,12,13,14,15,16 & 17], Marachi [18 & 19], Marsal [20 & 21], Varadarajan [22,13 & 24] to investigate the influencing factors on the mechanical failure of RFM. In addition, the research status and prospects of RFM mechanical property, dilatancy relation, and particle breakage are also described. Above researchers have been studied the effect of maximum particle size (d_{max}), confining pressure (σ_3), particle breakage (B), relative density (RD) and gradation of material on shear strength parameter i.e. angle of shearing resistance (ϕ) for rounded to sub-rounded and angular to sub-angular shape rockfill material. They observed that the behaviour of rounder to sub-rounded particle is different than the angular to sub-angular particle rockfill material.

2 Test Results of Large-scale triaxial tests& discussion

2.1 **Modeling of Rockfill material**

Due to the limitation of testing in the laboratory, the particle size of RFM was modeled and reduced to a smaller one by adopting parallel gradation technique (Lowe, 1964). Marsal [20, 21], Mirachi et al. [18,19], Gupta [3,4,5], Honkanadavar [6,7,8 & 9] and Varadarajan et al. [22,23 & 24]. Honkanadavar [6,7,8 & 9] carried out a series of large-scale triaxial tests to study thebehavior of RFM. They studied the dmax from 4.75 mm to 180 mm with specimen size of 2500 mm height and 600 mm diameter with a confining pressureranging from0.1 to 2.5 MPa,

2.1 Mechanical behavior

2.1.1 Strength

Strength of RFM depend on many parameters like composition of rock mineral, size of particle (max/min), shape (angular/sub-angular/rounded/ sub-rounded), gradation (well graded/ gap graded/ uniformly graded), relative density (loosest state / densest state) and surface texture (rough/smooth) of the rockfill particles (Varadarajan et at. [22,23]; Marachi et at. [18, 19], Honkanadavar et. al [7,8]. In this paper fives researchers results were taken for comparisons and those are highlighted. The angles of shearing resistance of RFM with different variables have been presented in graphical form. Variations of angle of shearing resistance of RFM with initial void ratio have shown in Fig 1. From the figures it is observed that the ϕ increases with decreases in void ratio.

Shear strength parameter of granular type of material mainly depends on shearing resistance among the particles (rolling & sliding) and particle interlocking. Cohesion characteristic is not prominent in rockfill as these materials are pervious in nature.

2.1.2 Research Studies

From the research review, it is observed that with the increases of confining pressure σ_3, the angle of shearing resistanceϕ of RFM decreases significantly for $\sigma_3 < 1$ MPa, while ϕ decreases at a controlled manner for $\sigma_3 > 1$ MPa, as shown in Fig. 2 for blasted rockfill materials (Varadarajan et at. [22,23 & 24]; Marachi et at. [18, 19], Honkanadavar et. al [6,7,8, 9 & 10]) due to particle breakage under high pressures, therefore, particle interlocking cannot be a component of the shear resistance. Marsal [20, 21] has shown that shearing resistance angle drastically changes from 57^o at $\sigma_3 <$ 1 MPa whereas Marachi (1969) has shown 36^o for $\sigma_3 > 1$ MPa.

Effect of interlocking on the shearing resistance (i.e., the friction angle) for angular to sub angular RMF decreases with increase $d_{max.}$ Due to more contact area and higher particle breakage, ϕ decreases with increases in for angular to sub-angular RMF (Fig. 3). However, due to less contact area and lesser particle breakage, ϕ increases with increases in d_{max} for rounded to sub rounded RFM (Fig 3).

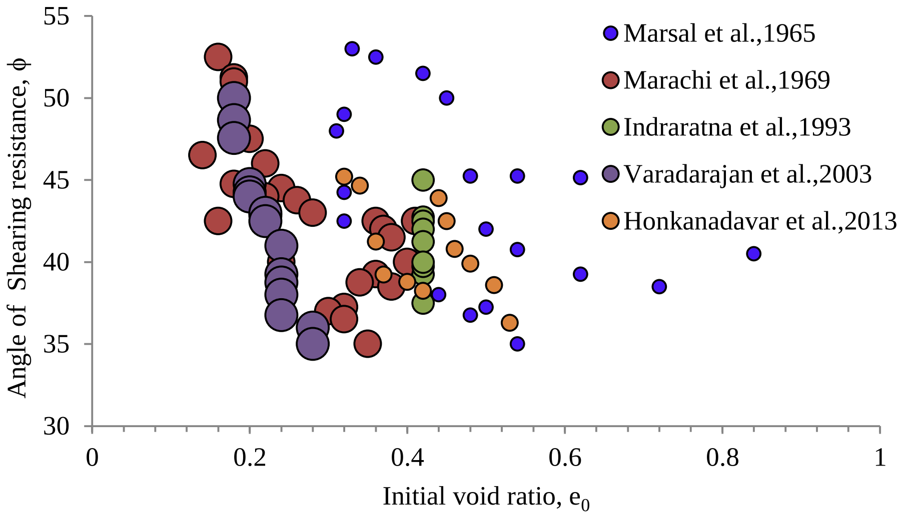

Fig. 1. Variations of angle of shearing resistance ϕ (degree) of RFM with initial void ratio

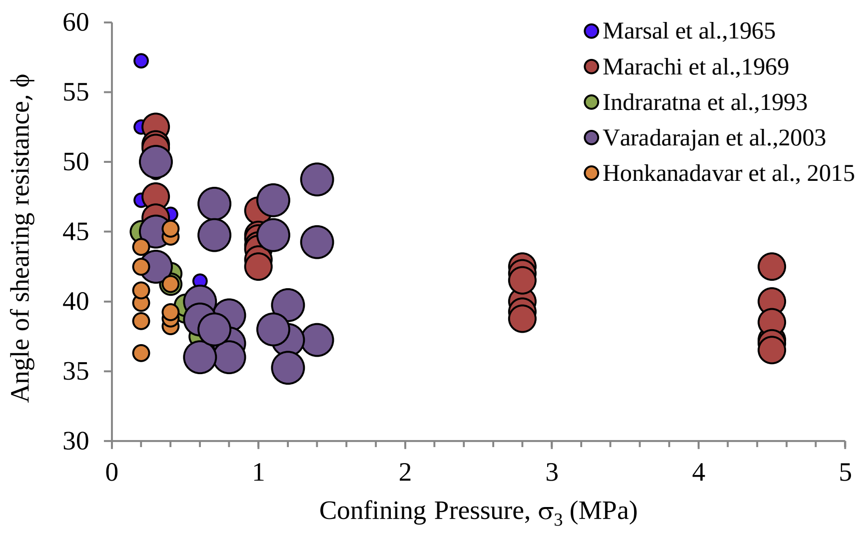

Fig. 2. Variations of angle of shearing resistance ϕ (degree) of RFM with confining pressure

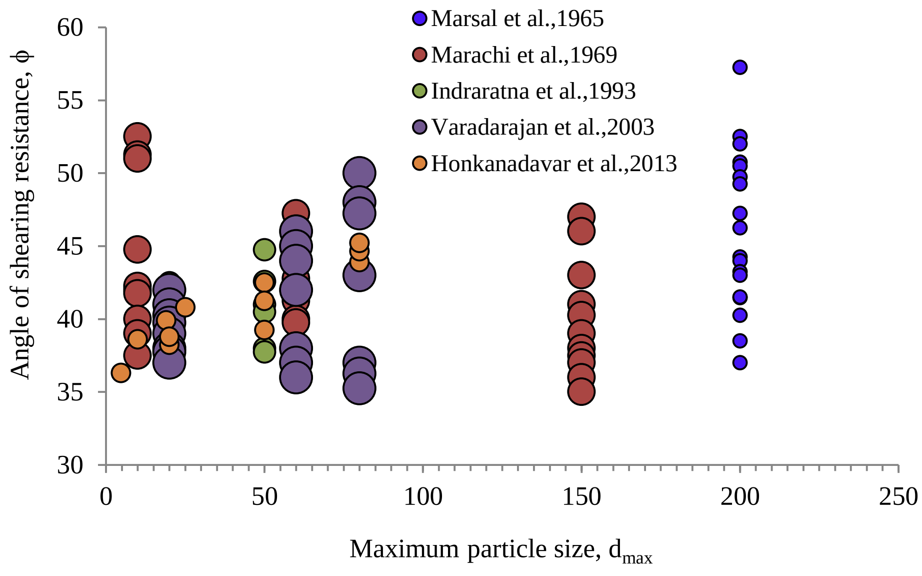

Fig. 3. Variations of angle of shearing resistance ϕ (degree) of RFM with maximum particle size

2.2. Dilatancy behavior

Dilatancy described of RFM by change in volume that is associated with shear distortion of the material. A suitable parameter for characterizing a dilatant of material is the dilatancy angle (ψ). This angle was introduced by Hansen (1958) and represents the ratio of plastic volume change over plastic shear strain (Vermeer et al. 1984) as:

$$\tan\psi = -\frac{de_v^p}{de_d^p} \quad (1)$$

The volumetric strain is calculated as

$$e_v = e_a + 2e_r \quad (2)$$

Where e_a represent axial strain and e_r represents lateral strain. In order to obtain volumetric plastic strain, e_v^p, it has been assumed that the sample is asymmetrical cylinder, the value of lateral plastic strain was considered proportional to axial plastic strain. Therefore, the lateral plastic strain represent as:

$$2e_r = (e_v - e_a)$$

$$e_r = (e_v - e_a)/2 \quad (3)$$

Finally, the volumetric plastic strain and plastic shear strain are as:

$$e_v^p = e_a^p + 2e_r^p \quad (4)$$

$$e_d^p = e_a^p - e_r^p \quad (5)$$

$$\tan\psi = \left\{-\frac{2de_v^p}{(3de_a^p - de_v^p)}\right\} \quad (6)$$

Frequently, separation of elastic and plastic components of strain is not straightforward, and total strain increments are used in calculation of dilative angle. For many situations, the contribution of elastic strains to total strains may be negligible when yielding is occurring, and the difference between a plastic strain increment ratio and a total strain increment ratio may be small (Wood 1990).Variations of the angle of shearing resistance of RFM with the dilatancy angle has been presented in Fig 4.

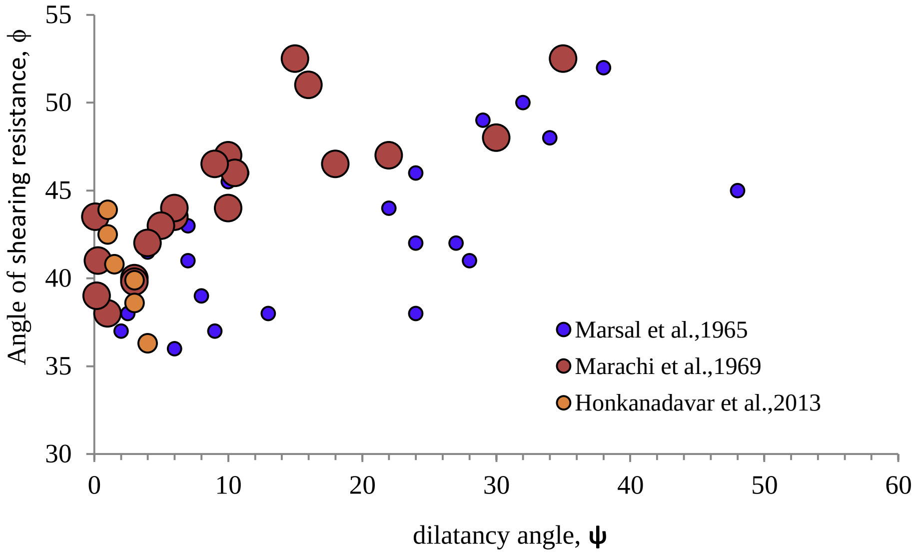

Fig. 4. Variations of the angle of shearing resistance of RFM with the dilatancy angle

2.3 Particle breakage behavior

Particle breakage index is divided in four ways based on process of analysis. Those are as follows:

- First method is particle size distribution (PSD) method, which is based on the differences of PSD before and after test.

$$\Delta W_s = \Delta W_{si} - \Delta W_{sf} \quad (7)$$

Where ΔWsi represents, the material retained on each sieve size 's' (in percent) before the test and ΔWsf represents the percent of material retained on the same sieve size i.e. 's' after the test. Further, breakage index or called as particle breakage factor is the sum of all negative or the positive values of ΔWs. Marshal's breakage index is presented as below (in percentage):

$$Bf = \sum (-\Delta Ws) = \sum (+\Delta Ws) \quad (8)$$

(take all positive or negative values)

- The second method is fine content (FC) method (d < 0.075 mm) (Miura et al., 2003).
- The third one is area method (Miura and Yamamoto, 1976; Miura and O-Hara, 1979; McDowell et al., 1996; McDowell and Bolton, 1998; Cristian, 2011; Fox, 2011; Russell, 2011),which is based on the increasing particle area during test and

- The last one is the discrete element method (DEM) (Cheng et al., 2003, 2004; Indraratna et al., 2013), which simulates particle breakage by a discrete element software.

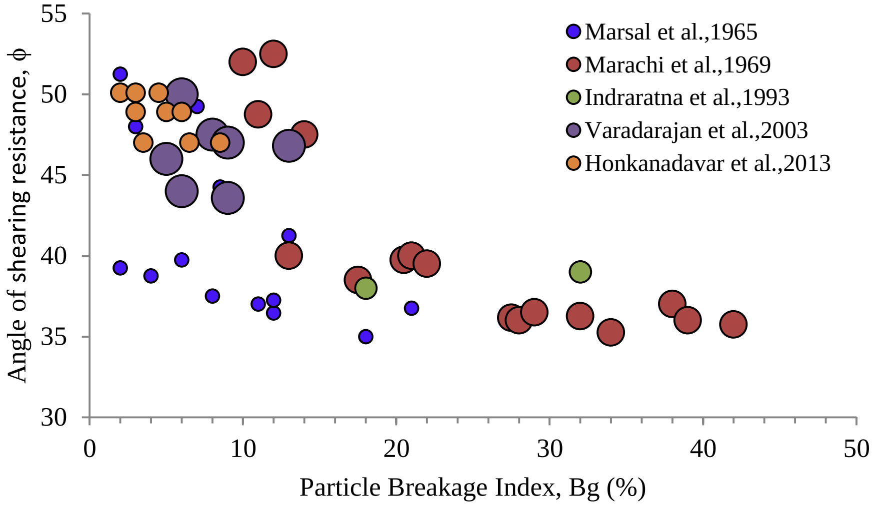

Fig. 5. Variations of shearing resistance of RFM with particle breakage index

Conclusions

Large-scale triaxial tests were summarized to investigate the research development of RFM on the mechanical property, dilatancy relation, and particle breakage. Confining pressure and particle breakage index play the most important roles in determining the strength of RFM. From the research and development of RFM, it is concluded that mechanical properties influence highly with the variation of relative density (D_r), moisture content, gradation, shape and size of particles. Confining pressure (σ_3) and particle breakage (B_g) play most important role in determining the strength of RFM. B_g of RFM varies with σ_3 and void ratio (e). From the dilation behaviour of RFM, it has been shown that, constitutive models based on elastic theory cannot predict the stress-strain-volume change behaviour properly as compared with the observed behaviour from laboratory testing. Therefore, the constitutive model based on elasto-plastic theory describes the stress-strain-volume change behaviour very closely with the observed behaviour from laboratory testing. Particle breakage one the important factor which degradation behaviour of RFM material under stress.

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