THE ROLE OF NATURE OF PARTICLES ON THE BEHAVIOUR OF ROCKFILL MATERIALS

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ABSTRACT

The nature of the particles of seven alluvial rockfill materials and three quarried rockfill materials are expressed in terms of uncompacted void content and unconfined compressive strength of each of the rockfill materials. Drained triaxial tests are conducted on modeled rockfill materials. The behaviour of the rockfill materials is related to the uncompacted void content and unconfined compressive strength of the rockfill materials. A prediction procedure is proposed to determine the angle of shearing resistance of the rockfill materials using uncompacted void content and unconfined compressive strength of these materials.

Key words: rockfill materials, triaxial tests, uncompacted void content, unconfined compressive strength (IGC: D3/D6)

INTRODUCTION

Rockfill dams are constructed using materials mostly obtained by blasting rocks in quarries. These materials consist of angular to subangular particles. Rockfill dams are also constructed with materials collected from riverbeds in some cases. Large quantities of these materials are available in the riverbeds of the tributaries of the major rivers, Ganges and Indus in India. These alluvial rockfill materials consist of rounded and subrounded particles as a result of impact, rolling and sliding action in the riverbed. Rockfill materials consist of particles as large as 1200 mm. It is known that the interparticle contact stresses increase with the size of the particles when they are subjected to loading in an engineering structure such as rockfill dam. The large contact stresses cause breakage of particles. The nature of particles such as shape and roughness also affect the breakage of particles. The behaviour of rockfill materials are affected by the breakage of particles besides all other factors that affect the behaviour of granular materials consisting of smaller sized particles.

As the sizes of the rockfill materials are large, some kind of modeling technique is often used to reduce the size of particles so that the samples prepared with smaller size particles can be tested. The material parameters from the tests are used to get the parameters for large size prototype particles by extrapolation using the size of the

particles as the basis. This procedure assumes implicitly that all the factors affecting the strength of the rockfill material can be related to the size of the particle. But, it is known that the factors such as shape, surface roughness and strength of the particles also affect the strength of the rockfill materials. This paper deals with laboratory testing of rockfill materials collected from ten project sites and correlation of the behaviour of these materials with various characteristics of the particles.

REVIEW

Particles of rockfill materials are primarily derived from quarries by blasting rock or collected from riverbeds. The characteristics of the particles are expressed by the mineralogy, size, shape and surface texture. The mineralogy depends on the parent rock from which the particle is derived. The size is defined by the size of the square hole in a screen of a sieve in Geotechnical Engineering. The rockfill particles are mostly equidimensional. The degree of roundness of the particles is qualitatively described as angular, subangular, subrounded, rounded and well rounded (Lambe and Whitman, 1969). Surface texture of the particle refers to minor features of a surface of a particle, independent of size, shape, or degree of roundness. Some terms used to describe surface texture are dull, polished, smooth or rough, striated, frosted, etched or pitted (Lambe and Whitman, 1969).

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Youd (1973) used the ratio of minimum radius of the particle edges to the inscribed radius of the entire particle to depict the roundness of the particle. Over the years several tests have been evolved for measuring coarse aggregate quality in Highway Engineering in terms of particle shape, angularity and surface texture. Standardised tests include percentage of fractured particles (ASTM D5821-1995), flat and/or elongated particles in coarse aggregates (ASTM D4791-1999), and index of particle shape and texture (ASTM D3398-2000). Alhrich (1996) proposed an uncompacted voids test for coarse aggregates and it is similar to the uncompacted voids test for fine aggregates (ASTM C1252-1998). This test is more objective and less labour intensive and less time consuming (Hossain et al., 2000).

Rockfill materials contain particles of large size and it is difficult to test them. Therefore, the size of the rockfill materials is reduced using modeling technique. Four modeling techniques are used to reduce the size of the rockfill materials viz. the scalping technique (Zeller and Wullimann, 1957), parallel gradation technique (Lowe, 1964), generation of quadratic grain size distribution curve (Fumagalli, 1969), and replacement technique (Frost, 1973). The parallel gradation technique was considered the most appropriate out of these four techniques (Ramamurthy and Gupta, 1986).

Rockfill materials have been tested using large scale triaxial testing equipment. Specimen diameter in these tests ranged from 15.2 mm to 500 mm, the maximum size of the particles ranged from 3.8 to 100 mm and the maximum confining pressure ranged from 0.69 to 13.8 MPa (Hall and Gordon, 1963; Marsal, 1967; Fumagalli, 1969; Marachi et al., 1972; Thiers and Donovan, 1981; Ansari and Chandra, 1986; Venkatachalam, 1993; Varadarajan et al., 2003). These researchers conducted tests on a wide range of rockfill materials. They have concluded that (i) the stress-strain behaviour of the rockfill material is nonlinear, inelastic and stress dependent, (ii) an increase in confining pressure causes increase in the value of peak deviatoric stress, axial strain and volumetric strain at failure, and (iii) an increase in the size of the particles results in an increase in volumetric strain at the same confining pressure. They found that the behaviour of the rockfill materials depends on mineral composition, particle size, shape, gradation, and relative density of the rockfill materials.

The material parameters for the large prototype size rockfill materials were obtained from the material parameters of the modeled rockfill materials using extrapolation techniques with the maximum particle size of the rockfill materials as the basis (Venkatachalam, 1993; Varadarajan et al., 2003).

SCOPE

The scope of the investigation was to determine the characteristics of the particles of the rockfill materials from various project sites, to conduct triaxial tests on modeled rockfill materials and to propose a procedure for

Fig. 1. Location of the project sites on the map

the prediction of the angle of shearing resistance for prototype rockfill materials using the characteristics of the particles.

ROCKFILL MATERIALS

Rockfill materials were collected from seven project sites in India. The locations of the projects are shown in Fig. 1. Six of the sites are located in the states of Punjab, Uttranchal, Uttar Pradesh and Haryana in the northern part of India. One site is in West Bengal state in the eastern part of India. Seven alluvial and three quarried rockfill materials were chosen for the study. A brief description of the location and the rocks are presented in Tables 1(a) and 1(b). The alluvial rockfill materials were from the beds of the tributaries of the two major rivers Ganges and Indus. Representative rockfill materials were collected from the project sites. The grain size distribution curves of all the materials are shown in Fig. 2. The maximum particle size ranges from 200 to 1200 mm. A wide range of gradation characteristics is observed in these materials.

The photographs of typical alluvial and quarried rockfill materials are shown in Figs. 3 and 4. Striking differences in composition and nature of particles are observed in the two types of rockfill materials. Whereas each alluvial rockfill material consists of rounded particles with rounded and smooth surfaces of various rock types, each quarried rockfill material consists of particles with angular and rough surfaces of same rock type.

Fig. 2. Grain size distribution curve for the rockfill materials

Table 1(a). Alluvial rockfill materials used

S. No.	Project name	Location	Name of the rocks
1.	Tehri Dam	Old Dobata borrow area, District Tehri Garhwal, Uttaranchal State	Quartzite, phyllite, sandstone, granite
2.	Tehri Dam	New Dobata borrow area, District Tehri Garhwal, Uttaranchal State	Quartzite, phyllite, shale, limestone
3.	Kol Dam	Kol, District Bilaspur, Himachal Pradesh State	Quartzite, limestone, shale, sandstone
4.	Ranjit Sagar Dam	Shahpur Kandi, District Gurdaspur, Punjab State	Quartzite, jasper, shale, conglomerate, claystone, sandstone, grits of chart
5.	Shah Nehar	At running distance (RD) 7410, near Sansarpur Terrace, District Kangra, Himachal Pradesh State	Micaceous sandstone, quartzite
6.	Western Yamuna Canal	Foundation of bridge, District Yamuna Nagar, Haryana State	Quartzite, marble, limestone
7.	Western Yamuna Canal	Foundation of silt ejector site, District Yamuna Nagar, Haryana State	Quartzite, limestone, shale, sandstone, phyllite

Table 1(b). Quarried rockfill materials used

S. No.	Project name	Location	Name of the rock
1.	Kol Dam	Kol, District Bilaspur, Himachal Pradesh State	Limestone
2.	Purulia Dam	Purulia, West Bengal State	Hornblende-quartz-schist
3.	Parbati Dam	Kartah quarry, Sainj, District Kullu, Himachal Pradesh State	Quartzite

NATURE OF PARTICLES

The nature of the particles primarily refer to size, shape, surface texture and mineralogical composition of the particles. The sizes of the particles and their distribution in a rockfill material are determined by sieve analysis.

The shape, surface texture and gradation of fine aggregates are quantitatively expressed by a single property known as Uncompacted Void Content (UVC) (ASTM C1252-1998). The same concept, which has been extended to coarse aggregates by Alhrich (1996) and Hosain et al. (2000), has been adopted herein for rockfill materials. The test apparatus proposed by Alhrich (1996) was fabricated and is shown in Fig. 5(a). With this apparatus, material with maximum particles size of 19.0 mm can be tested. The apparatus and the test procedure are briefly described in the following.

The apparatus consists of a top and a bottom cylinder. The bottom cylinder called cylindrical measure, is one side open on the top. The top cylinder which functions as a funnel, is fitted with a conical cylinder at the bottom. The opening at the bottom is provided with a lid which can be opened suddenly to pour the material in the cylindrical measure (Fig. 5(b)).

The upper cylinder is filled freely with 5 kg of rockfill material after striking off the excess material. The bottom lid is suddenly opened to allow the material to freely fall

Fig. 3. Alluvial rockfill materials obtained from bridge site, Western Yamuna Canal

Fig. 4. Quarried rockfill materials obtained from Kol Dam Site

in the cylindrical measure. The material collected is weighed after leveling the surface. The UVC is calculated as:

$$UVC = \frac{V - F/G}{V} \times 100 \quad (1)$$

where,

V = Volume of the material collected in the cylindrical measure in ml,

F = Net weight of the material collected in cylindrical measure in gm,

G = Specific gravity of the material

To study the effect of size, three modeled rockfill materials with maximum sizes of 19.00, 9.50 and 4.75 mm were prepared from each rockfill material using parallel gradation technique (Lowe, 1964). The values of UVC for each material were determined. Semi log plots between the maximum particle sizes of the modeled materials and UVC were plotted. Typical plots for two rockfill materials from Ranjit Sagar dam site and Purulia dam site are shown in Fig. 6. The plots are found to be linear and may be used to determine the value of UVC for larger particle sizes as shown in Fig. 6. In Fig. 6, it is observed that the value of UVC decreases with increase in

Fig. 5(a). Apparatus used to determine Uncompacted Void Content

Fig. 5(b). Line diagram of UVC apparatus

the maximum particle size. Also the value of UVC for Ranjit Sagar material is less than that for Purulia material for the same maximum particle size. Lower value of UVC indicates more material (particles) per unit volume (i.e. higher density) (Eq. (1)).

A material having different average particle sizes but with same uniformity coefficient (i.e. parallel gradation) and shape and surface texture will attain lower void ratio with larger average particle size, provided the compaction effort is same (Lambe and Whitman, 1969). The decrease in the UVC value with increase in particle size observed in this study (Fig. 6) also confirms this finding.

Ranjit Sagar and Purulia rockfill materials are well graded with uniformity coefficient 131 and 15 respectively. But, for the same maximum particle size, Purulia rockfill material shows higher value of UVC than Ranjit Sagar rockfill material (Fig. 6). This may be attributed to the fact that the particles of Purulia rockfill material with angular and rough surfaces attain lower density (higher UVC) than the particles of Ranjit Sagar rockfill material with rounded and relatively smooth surfaces. Therefore,

Fig. 6. Typical plot of uncompacted void content vs maximum particle size

the value of UVC may also be used for comparing the shape and surface characteristics of the particles between two rockfill materials having similar gradation curves. Thus, the value of UVC may be used to quantitatively represent size as well as shape and surface characteristics of particles.

Individual particle strength is one of the factors that affect the shear strength of granular materials and the rockfill materials in particular as the particle is subjected to high interparticle stresses during shearing. In this study, the strength of the particle is represented by the Unconfined Compressive Strength (UCS) of the rock from which the particle is derived. The UCS value for each rockfill material is determined as follows.

Blocks of representative rock were collected from the project sites. At least five cylindrical specimens of sizes 38.1 mm in diameter and 76.2 mm in length were cored from the rock. Each specimen was tested in a compression testing machine with a constant stress rate of 0.5 to 1.0 MPa/s till failure (ASTM D2938-95). The failure load as expressed in stress is the UCS of the specimen. An average of UCS values of the five specimens is taken as the UCS value of the rock.

Three modeled rockfill materials with maximum particle sizes 25, 50 and 80 mm were obtained using parallel gradation technique (Lowe, 1969) for each rockfill material. Typical gradation curves for the modeled materials of a rockfill material are shown in Fig. 2. These modeled materials were used later in triaxial tests. The values of UVC for these maximum particle sizes were obtained by extrapolation from the UVC values already determined for smaller maximum particle sizes.

The values of UVC were plotted against the values of UCS for all the modeled rockfill materials as shown in Fig. 7. As observed earlier, it is found that the values of UVC decreases with increase in particle size and the value of UVC is high for quarried rockfill material as compared to the value of UVC for alluvial rockfill material for the same maximum particle size.

An abrasion test was also conducted on the rockfill particles to determine Los Angeles Abrasion Value (IS: 2386: Part 4: 1963). In this test an aggregate of 5 kg weight (20–12.5 mm size, 2.5 kg and 12.5–10 mm size,

Fig. 7. Variation of UVC with UCS for alluvial and quarried rockfill materials

2.5 kg) is loaded in a drum of 700 mm diameter and 500 mm length along with abrasive charge consisting of 11 cast iron balls. The drum is rotated about its axisymmetric axis on the vertical plane at a speed of 30 to 33 rpm upto 500 revolutions. The aggregate is then taken out and sieved through 1.7 mm Indian Standard (IS) sieve. The Los Angeles Abrasion value, expressed in percentage, is calculated from the ratio of the material passed through 1.7 mm IS sieve of total weight of the material taken. The Los Angeles Abrasion value (LAV) for alluvial rockfill materials are also plotted in Fig. 7. It is remarkable to note that the nature of variation of LAV of the alluvial materials with respect to UCS is similar to that of UVC. The LAV of quarried materials also showed similar behaviour (not shown in figure).

It is noted in Fig. 7 that there is scatter of points and there is no specific trend for various alluvial rockfill materials in the plot between UCS and UVC/LAV. The value of UVC for an alluvial rockfill material is dependent on the roundness and the smoothness besides the size of the particles. Increased roundness and smoothness will result in reduction in the UVC value for the rockfill material consisting of same sized particles. The degree of roundness and smoothness may not be same for all the alluvial rockfill materials. The alluvial rockfill materials considered in this study are derived from the rocks of Himalayas and are the product of the riverbed action during water flow in the tributaries of the major rivers Indus and Ganges (Fig. 1). These snow-fed rivers carry broken rock pieces of various sizes produced primarily by glaciation and weathering of rocks/boulders. The impact, rolling and sliding actions of the rock pieces in the riverbed during water flow cause roundness and smoothness to the rock pieces. The riverbed-actions on the rock pieces depend essentially on the velocity of water flow and the nature of the riverbed. As these actions are not same for all the rivers, the roundness and smoothness of the rock particles are different for each rockfill material and this is reflected in the scatter of the points in the plots between UCS and UVC/LAV observed in Fig. 7 for various alluvial rockfill materials.

Table 2. Details of drained triaxial tests

S. No.	Materials from	Maximum particle size, $d_{\max}$ (mm)	Confining pressure, σ_3 (MPa)
1.	Ranjit Sagar Dam Site	25, 50, 80	0.35, 0.70, 1.10, 1.40
2.	Tehri Dam Site (both borrow areas)	25, 50, 80	0.352, 0.704, 1.056, 1.408
3.	Western Yamuna Canal (both sites)	25, 50, 80	0.2, 0.4, 0.6, 0.8
4.	Shah Nehar Site	25, 50, 80	0.2, 0.4, 0.6, 0.8
5.	Kol Dam Site (both materials)	25, 50, 80	0.3, 0.6, 0.9, 1.2
6.	Purulia Dam Site	25, 50, 80	0.3, 0.6, 0.9, 1.2
7.	Parbati Dam Site	20, 40, 80	0.3, 0.6, 0.9, 1.2

Table 3. Details of the triaxial cell

Particulars	Applied by	Capacity
Confining pressure	Air-water pressure system	3 MPa
Axial load	Hydraulic pressure unit	875.7 kN
Specimen size	Length = 813 mm, Diameter = 381 mm	

In Fig. 7, it is noted that between the two rockfill materials from Tehri dam site (points corresponding to UCS values 106.47 and 136.96 MPa) the material with higher UCS shows lower UVC/LAV though they belong to the same area and might have been subjected to similar riverbed action. As such, it appears that the effect of riverbed action on the material with higher UCS is more than the one with lower UCS for comparable riverbed action. Therefore, it is probable that there is a general trend, as shown by average linear lines in Fig. 7, that as UCS increases UVC decreases provided the riverbed action is similar for all the alluvial rockfill materials.

TRIAXIAL TESTS

Consolidated drained triaxial tests were conducted on the modeled rockfill materials. A dry density corresponding to 87% of relative density was adopted for testing. The confining pressure ranges for the tests were chosen depending upon the dam/abutment height in each project. Details of the tests are presented in Table 2.

Large size triaxial testing facility at the Central Soil and Materials Research Station, New Delhi, India, a Government of India Research Station which provides laboratory and field testing services for most of the river valley projects in the country, was used for testing. Specimen size of 381 mm in diameter by 813 mm in length was used for testing. Details of the triaxial cell used for the specimen size is shown in Fig. 8. Details of the equipment used are given in Table 3.

The complete details of the experimental procedure are

Fig. 8. Triaxial test setup

given by Abbas (2003). A brief description of the experimental procedure is presented in the following.

The quantity of various sizes of rockfill materials required to achieve the gradation of the modeled rockfill material for preparing the specimen at specified relative density was determined by weight. The sample was prepared using a split mould. The sample was prepared in five layers in the split mould by compacting each layer by a vibrator. The sample was saturated by allowing water to pass through the base of the triaxial cell, and using a top drainage system for removing air voids. The sample was subjected to the required consolidation pressure and then sheared by applying axial loading with a rate of loading of 1 mm/min. Readings of vertical displacement, volume change, and axial loads were recorded at periodic intervals.

EXPERIMENTAL RESULTS

Stress-Strain-Volume Change Relationships

Stress-strain-volume change relationships of the modeled alluvial rockfill materials are shown in Figs. 9 to 15. It is observed that, in general, axial strain at failure increases with increase in confining pressure and maximum particle size. Volume change response shows compression for three of the alluvial rockfill materials from Tehri dam site (Old Dobata), Kol dam site, and Ranjit Sagar dam site. The volume compression increases with confining pressure and maximum particle size in these materials. Three of the remaining alluvial rockfill materials from Shah Nehar site, and Western Yamuna

(i) Stress-Strain Behaviour

(ii) Volume Change Behaviour

(i) Stress-Strain Behaviour

(ii) Volume Change Behaviour

Fig. 9. Stress-strain-volume change behaviour of alluvial rockfill material obtained from old dobata borrow area, Tehri Dam Site

Canal (Bridge site and Silt Ejector site) show volume compression initially and some dilation latter during shearing. The dilation nearly vanishes with increase in confining pressure and maximum particle size. The net volumetric strain is compressive in all the cases. The rockfill material from Tehri dam site (New Dobata) shows mixed trend in the volume change behaviour.

Stress-strain-volume change relationships of the three quarried rockfill materials are shown in Figs. 16 to 18. In these materials also, axial strain at failure increases with confining pressure as well as maximum particle size. All the quarried materials show compression in the initial part of shearing and dilation in the later part of shearing. The dilation in volumetric strain decreases considerably with increase in confining pressure and the maximum particle size.

Effect of UVC and UCS on Breakage Factor

Breakage of particles was observed during triaxial tests. The breakage is expressed quantitatively by the

Fig. 10. Stress-strain-volume change behaviour of alluvial rockfill material obtained from new dobata borrow area, Tehri Dam Site

breakage factor, B_g . The value of B_g is calculated by sieving the sample using a set of sieves (80 to 0.075 mm) before and after testing. The percentage of particles retained in each sieve is determined at both stages. Due to breakage of particles, the percentage of particles retained in large size of sieves will decrease and the percentage of particles retained in small size sieves will increase. The sum of decreases will be equal to the sum of increases in the percentage retained. The decrease (or increase) is the value of the breakage factor B_g (Marsal, 1967).

The relationships between UCS and B_g for all the modeled rockfill materials with the maximum particle size of 50 mm for three confining pressures, 0.4, 0.6 and 0.8 MPa are shown in Fig. 19. It is observed that the breakage increases with increase in confining pressure, σ_3 for both alluvial and quarried rockfill materials. The increase in confining pressure causes an increase in contact stresses leading to an increase in particle break-

(i) Stress-Strain Behaviour

(ii) Volume Change Behaviour

Fig. 11. Stress-strain-volume change behaviour of alluvial rockfill material obtained from Ranjit Sagar Dam Site

(i) Stress-Strain Behaviour

(ii) Volume Change Behaviour

Fig. 12. Stress-strain-volume change behaviour of alluvial rockfill material obtained from Shah Nehar Site

age.

In Fig. 19 it is also noted that the quarried rockfill materials with higher UVC values (Fig. 7) show higher B_g values than the alluvial rockfill materials. The higher UVC values in the quarried rockfill materials are due to angular and rough particles as observed earlier and as a consequence they undergo higher breakage than the alluvial rockfill materials.

The rate of increase of B_g with σ_3 is shown in Fig. 20 for the same materials. It is found that the quarried rockfill materials having particles of angular and rough surface show higher rate of breakage than the alluvial rockfill materials having particles of rounded and smooth surface.

The effect of maximum particle size on B_g is shown in Fig. 21 for the samples tested at the same σ_3 equal to 0.8 MPa. It is observed that the breakage increases with the increase in the maximum particle size for both types of rockfill materials. With the increase in the size of the particles, the value of UVC decreases indicating increase

in density (Fig. 6). Increase in density causes increase in interparticle contact stresses leading to increased particle breakage. Similar effects of size of the particles and confining pressure on breakage factor were observed by Marsal (1965), Vesic and Clough (1968), Marachi et al. (1969), Venkatachalam (1993) and Varadarajan et al. (2003).

As the breakage factor is related to the UVC, the scatter of points observed in Figs. 19 and 21 is attributed to the scatter of the points in the relationship between UCS and UVC in Fig. 7 for the alluvial rockfill materials. Also, the average lines indicated in these figures correspond to the average lines shown in the relationship between UCS and UVC in Fig. 7.

Effect of UVC and UCS on Volumetric Strain

The effects of the maximum particle size and the confining pressure on the volumetric strain at failure are shown in Figs. 22 and 23 for the two types of rockfill materials. It is observed that volumetric strain at failure

(i) Stress-Strain Behaviour

(ii) Volume Change Behaviour

(i) Stress-Strain Behaviour

(ii) Volume Change Behaviour

Fig. 13. Stress-strain-volume change behaviour of alluvial rockfill material obtained from Bridge Site, Western Yamuna Canal

Fig. 14. Stress-strain-volume change behaviour of alluvial rockfill material obtained from Silt Ejector Site, Western Yamuna Canal

increases with maximum particle size and the confining pressure for both the materials. These findings on volumetric strain at failure are, in general, similar to those noted for breakage factor. That is, lower the UVC, higher is the breakage factor leading to higher volumetric strain at failure. As noted in the previous section, the scatter in the points in the relationship between UCS and B_g in Figs. 19 and 21 is related to the scatter of points in the relationships between UCS and UVC in Fig. 7 for the alluvial materials. Therefore, the scatter of points observed in Figs. 22 and 23 is also due to the scatter of points in Fig. 7.

Angle of Shearing Resistance ϕ

From the stress-strain curves the values of $(\sigma_1 - \sigma_3)$ at failure for each confining pressure, σ_3 , were determined and with these values the plots of $p = (\sigma_1 + \sigma_3)/2$ vs $q = (\sigma_1 - \sigma_3)/2$ were made for each rockfill material as shown in Fig. 24 for typical alluvial (Old Dobata, Tehri Dam) and quarried (Purulia Dam) rockfill materials. The

failure envelopes for each maximum particle size of rockfill material passed through the origin as shown in the Fig. 24 for the typical rockfill materials. From the angle of the slope, α of the failure envelope, the angle of shearing resistance, ϕ was calculated as $\phi = \sin^{-1}(\tan \alpha)$ (Lambe and Whitman, 1969) for each rockfill material.

Effect of Particle Shape on ϕ

The variation of ϕ with UCS is shown in Fig. 25 for the three sizes of modeled alluvial and quarried rockfill materials. It is observed that the values of ϕ for quarried materials are higher than those for alluvial materials. The quarried rockfill materials with higher value of UVC (Fig. 7) are looser than the alluvial rockfill materials. Therefore, a looser quarried rockfill material would provide lower interlocking resistance during shearing than an alluvial rockfill material. However, the nature of particle shape and surface texture also affect the interlocking resistance during shearing. Higher value of UVC for quarried material also indicates more angular

(i) Stress-Strain Behaviour

(ii) Volume Change Behaviour

Fig. 15. Stress-strain-volume change behaviour of alluvial rockfill material obtained from Kol Dam Site

(i) Stress-Strain Behaviour

(ii) Volume Change Behaviour

Fig. 16. Stress-strain-volume change behaviour of quarried rockfill material obtained from Kol Dam Site

and rougher particles than the alluvial rockfill material as already noted in Fig. 7. Due to this, quarried rockfill material would provide higher interlocking resistance during shearing than the alluvial rockfill material. Furthermore, in the case of quarried rockfill materials the dilatancy caused by the angular and rough particles during shearing as shown by the volume change behaviour in Figs. 16, 17 and 18 leads to higher shearing resistance. Considering the net effects of density and nature of the particles for the two types of rockfill materials, it is evident that the effect of shape and surface texture of particle is more dominant than the effect of the density of the rockfill material leading to higher angles of shearing resistance for the quarried rockfill materials than those for the alluvial rockfill materials.

Effect of Particle Size on ϕ

In Fig. 25, it is observed that the ϕ value decreases with the maximum particle size for quarried rockfill material and it increases with the maximum particle for alluvial rockfill material. Venkatachalam (1993) and Varadarajan

et al. (2003) have shown that the ϕ value increases with the increase in maximum particle size for alluvial rockfill materials. Marachi et al. (1969) and Varadarajan et al. (2003) have reported decrease in the ϕ value with increase in maximum particle size for quarried rockfill materials. As shown in Fig. 7, the value of UVC decreases with the increase in maximum particle size for both alluvial and quarried rockfill materials. A larger sized rockfill material with lower value of UVC would be denser and would exhibit higher interlocking resistance during shearing. It is observed from Fig. 21 that larger sized rockfill materials with lower UVC value also undergo higher breakage during shearing. The effect of breakage is to reduce the resistance during shearing. Therefore, the net effect of denseness and breakage on shearing resistance will decide the nature of change of ϕ with respect to the increase in the maximum particle size. It is noted that the rate of average increase in breakage factor with increase in confining pressure is higher for quarried rockfill materials than that for alluvial rockfill materials

(i) Stress-Strain Behaviour

(ii) Volume Change Behaviour

(i) Stress-Strain Behaviour

(ii) Volume Change Behaviour

Fig. 17. Stress-strain-volume change behaviour of quarried rockfill material obtained from Parbati Dam Site

Fig. 18. Stress-strain-volume change behaviour of quarried rockfill material obtained from Purulia Dam Site

(Fig. 20). Therefore, the effect of breakage on the shearing resistance of quarried rockfill material is higher than that for alluvial rockfill material. Therefore, the effect of breakage on the ϕ value appears to be more dominant in the case of quarried rockfill materials than that in the case of alluvial rockfill materials. Therefore, the value of ϕ decreases with the increase in the maximum particle size for quarried rockfill materials whereas the value of ϕ increases with the increase in the maximum particle size for alluvial rockfill materials as shown in Figs. 25 and 26.

Effect of UCS on ϕ

The average rate of change of ϕ values with respect to maximum particle size has been plotted with UCS values for both types of the rockfill materials as shown in Fig. 27. It is significant to note that the value of ϕ as well as the average rate of increase in the value of ϕ with respect to maximum particle size increase with the increase in the UCS value for alluvial rockfill materials as shown in Figs. 26 and 27. As already observed in Figs. 7

Fig. 19. Variation of B_g with UCS for the two types of rockfill materials

and 21, on the average, the value of UVC decreases (denseness increases) with the increase in the UCS value and the breakage factor increases with the increase in the

Fig. 20. Variation of average rate of change of B_g with respect to σ_3 with UCS

Fig. 21. Variation of B_g with UCS for the two types of rockfill materials

Fig. 22. Variation of volumetric strain at failure with UCS at three confining pressures

UCS value for the alluvial rockfill materials (Figs. 19 and 21). As discussed in the previous section, the effect of increase in denseness (lower UVC value) is to increase the shearing resistance during shearing due to higher interlocking, but the effect of increase in denseness is also to decrease the shearing resistance due to the damage caused by high breakage of particles. It appears that the effect of denseness in increasing the shearing resistance during shearing is more dominant than the effect of breakage of

Fig. 23. Variation of volumetric strain at failure with UCS at three maximum particle sizes

Fig. 24. p - q diagram for typical alluvial and quarried rockfill materials

Fig. 25. Variation of ϕ -value with maximum particle size

particles in decreasing shearing resistance. As a result, the ϕ value as well as the rate of increase in ϕ value with respect to the maximum particle size increases with the UCS value. With regard to quarried rockfill materials, it has not been possible to arrive at any conclusion on the effect of UCS due to limited data.

PREDICTION OF ϕ FOR PROTOTYPE ROCKFILL MATERIAL

Shear strength of geologic materials has been expressed

Fig. 26. Variation of ϕ -value with UCS of three maximum particle sizes

Fig. 27. Variation of average rate of change of ϕ -value with respect to confining pressure with UCS

as a functional relationship between shear strength and normal stress or principal stresses by various researchers following Mohr-Coulomb failure criterion (deMello, 1977; Yoshinaka and Yamabe, 1981; Franklin and Dusseault, 1989; Ramamurthy, 2001). Herein, the following relationship is proposed for the rockfill materials tested under triaxial condition

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

where, B' is a non-dimensional parameter based on index properties of the rockfill materials, α' is non-dimensional parameter, σ_1 and σ_3 are the major and minor principal stresses and p_a is atmospheric pressure expressed in the same unit as the principal stresses.

The parameter, α' can be determined by conducting at least two triaxial tests with two different confining pressures as:

$$\alpha' = \frac{\log \frac{(\sigma_1 - \sigma_3)_i}{(\sigma_1 - \sigma_3)_{i+1}}}{\log \frac{(\sigma_1 + 2\sigma_3)_i}{(\sigma_1 + 2\sigma_3)_{i+1}}} \quad (3)$$

where subscripts i and $i+1$ indicate two triaxial tests.

The values of α' were determined for all the modeled

rockfill materials from the triaxial test results. The value of α' was found to be nearly constant and was equal to 0.937.

The parameter B' has been expressed as a function of the basic characteristics of the rockfill materials that affect their behaviour. These characteristics include particle size, nature of particle shape and surface, particle strength, gradation and relative density. In this study, the particle size, the nature of particle shape and surface and gradation are expressed in terms of UVC and the particle strength is represented by the UCS of the representative rock from which the particles are derived. Accordingly, the value of B' is expressed as:

$$B' = C_1 P^{p_1} + C_2 (UVC)^{p_2} \quad (4)$$

where C_1 , C_2 , p_1 and p_2 are constants,

P normalized UCS value. In this study the UCS is normalized with UCS value of Ranjit Sagar rockfill material which is the highest value. Any other value could have also been used for normalization,

UVC uncompact void content expressed as fraction. The relative density has not been included in the above relationship (Eq. (4)) as all the modeled rockfill materials were tested with the same relative density.

The values of the constants C_1 , C_2 , p_1 and p_2 were determined as follows.

The value B' was determined using Eq. (4) at four confining pressures for each modeled rockfill material. The average of four values was calculated. This value was used in Eq. (2) along with the values of P and UVC of that material. Thus three equations were formed for the three modeled materials for each rockfill material. Twenty one of such equations were formed for seven alluvial rockfill materials and nine equations were formed for the three quarried rockfill materials. The four constants C_1 , C_2 , p_1 and p_2 were found using least squares fitting method for alluvial and quarried rockfill materials separately. With these constants, the relationships for the prediction of the B' value were found to be:

$$B' = 0.85016P^{0.2} - 2.14964(UVC)^{2.4} \quad (5)$$

for alluvial rockfill materials and,

$$B' = 0.58072P^{0.1} + 0.59167(UVC) \quad (6)$$

for quarried rockfill materials.

The validity of these Eqs. (5) and (6) was verified as follows:

Using the Eqs. (5) and (6), the value of B' was predicted for each modeled rockfill material. The values of σ_1 at failure were then predicted using Eq. (2) for the four confining pressures, σ_3 used in the triaxial tests. From these values of σ_1 and σ_3 at failure, the value of ϕ was calculated. The values of ϕ predicted for all the modeled rockfill materials have been compared with the observed values from the tests in Figs. 28 and 29. It has been observed that the error between the predicted and observed ϕ -value is in the range of -8 to $+12$ (%). As such the prediction may be considered satisfactory. Using

Fig. 28. Comparison of observed and predicted ϕ -values for alluvial rockfill materials

Fig. 29. Comparison of observed and predicted ϕ -values for quarried rockfill materials

Table 4. Comparison of ϕ -values of prototype rockfill materials

Material site		ϕ -values based on power law (degree)	ϕ -values based on index properties (degree)	Difference in ϕ -values (degree)	Difference (%)
Alluvial	Tehri Dam (Old Dobata)	51.4	41.9	-9.6	-18.68
	Tehri Dam (New Dobata)	46.2	39.7	-6.5	-14.07
	Kol Dam	41.6	36.3	-5.3	-12.74
	Ranjit Sagar Dam	63.3	45.7	-17.6	-27.80
	Shah Nehar	43.2	40.5	-2.7	-6.25
	Western Yamuna Canal (Bridge Site)	50.3	43.4	-6.9	-13.72
	Western Yamuna Canal (Silt Ejector Site)	45.8	43.5	-2.3	-5.02
Quarried	Kol Dam	38.8	42.3	3.5	9.02
	Purulia Dam	37.1	38.8	1.7	4.58
	Parbati Dam	40.4	40.0	-0.4	-0.99

Eqs. (5) and (6), the values of ϕ were predicted for an alluvial obtained from Pancheshwar Hydro-electric Power Project, Nepal and a quarried rockfill material obtained from Middle Siang Hydro-electric Power Project, Arunachal Pradesh (materials not included for the determination of constants in Eqs. (5) and (6)) and are shown in Figs. 28 and 29. The predictions appear quite satisfactory.

As more data are available with time, constants in Eqs. (5) and (6) may be further refined. Equations (5) and (6) can then be used with confidence to predict the angle of shearing resistance of rockfill materials for the design of dams.

The value of ϕ for prototype size rockfill material was determined with the Eq. (2) using B' values as calculated from Eqs. (5) and (6) for the corresponding values of UVC of the prototype size. The values of ϕ predicted for a prototype size of 300 mm for all the rockfill materials are presented in Table 4. For comparison, the values of ϕ were predicted for all the rockfill materials using the commonly used extrapolation technique using power law (Varadarajan et al., 2003). Significant differences are noted between the predicted ϕ values by the two procedures. It is believed that the ϕ values predicted by the procedure used in the present study is realistic as it includes most of the basic characteristics of the rockfill

material whereas the common extrapolation procedure used considers only the maximum particle size of the rockfill material.

CONCLUSIONS

The characteristics of particles from seven alluvial rockfill materials and three quarried rockfill materials have been quantitatively expressed by uncompacted void content and unconfined compressive strength of the rock particles. Decrease in the uncompacted void content with the maximum particle size and average decrease in the uncompacted void content with unconfined compressive strength of the particles are observed. Angular and rough surfaced particles of quarried rockfill materials are found to have higher uncompacted void content than the round and smooth surfaced particles of alluvial rockfill materials.

From the drained triaxial tests on the modeled rockfill materials of alluvial and quarried rockfill materials, the following conclusions are drawn.

- i) The axial strain, volumetric strain and breakage factor increase with confining pressure and maximum particle size.
- ii) The average rate of breakage factor with confining pressure is higher for quarried rockfill material than that for alluvial rockfill material.
- iii) The angles of shearing resistance for quarried rockfill materials are higher than those for alluvial rockfill materials with comparable unconfined compressive strength of rock particles.
- iv) The angle of shearing resistance for alluvial rockfill materials increases with the maximum particle size and opposite trend is noted for quarried rockfill materials.
- v) The angles of shearing resistance as well as the rate of increase in angle of resistance with maximum particle size increase with the increase in the unconfined compressive strength of the rock particles for alluvial rockfill materials.
- vi) The behaviour of rockfill materials, in general, may be explained in terms of the uncompacted void content and unconfined compressive strength of the rock particle.
- vii) A relationship has been developed to predict the angle of shearing resistance of modeled rockfill materials using the uncompacted void content of the rockfill materials and unconfined compressive strength of the rock particles. It is believed that this method is superior to the existing method based on maximum size of particles and may be used to predict the angle of shearing resistance of prototype size rockfill materials. It has potential to be used for the prediction of the angle of shearing resistance for the design of rockfill dams.

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