A Review of Shear Resistance of Rockfill Using Large Scale Shear Tests

Kaveh Dehghanian[1,] Sayed Mansoor ZAFAR[2,] Emrah ÇALTILI[3]
Beste KOÇAK DİNÇ[4,] Hakan Murat SOYSAL[5]

Abstract: Earth and rockfill dams, because of their special characteristics compared to concrete dams, are widely used in construction throughout the world. Rockfill dams are more flexible, have capacity to absorb large seismic energy, and adaptability to various foundation conditions. The use of modern earth and rock equipment and locally available materials make such dams economical as well. Therefore, improving the knowledge of experts about the design and maintenance of these dams are vital. Different reports of settlement and deformation of operating rockfill dams depict the importance of technique improvements and designing new test apparatus to monitor them.

The behavior of these materials, specifically their shear strength are not fully understood. Several types of laboratory devices have been developed to estimate the strength of these materials. Among these devices, direct shear test has been employed most commonly owing to its simplicity and low-cost compared to triaxial and other methods. Traditional laboratory direct shear tests are not appropriate for investigation of rockfill materials which have large-sized particles. In this case, laboratory large scale direct shear tests are required to be performed on these materials. In this paper, a brief review of parameters affecting shear resistance of these particles and a history of large scale tests are presented.

Keywords: *Shear strength, direct shear test, rockfill material, shear resistance*

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[1]Assistant Professor, Civil Engineering department, Istanbul Aydın University, Turkey
Corresponding author: kavehdehghanian@aydin.edu.tr
[2]Msc Student, Civil Eng. Department, Istanbul Aydin University, Istanbul, Turkey
[3]Professional Engineer, Civil Engineering department, Istanbul Aydın University, Turkey
[4]Professional Engineer, Civil Engineering department, Istanbul Aydın University, Turkey
[5]Geological Engineer, Civil Engineering department, Istanbul Aydın University, Turkey

1.Introduction

Testing large granular particles require a large test apparatus to avoid scale effects related to the size of particles compared to the dimension of test apparatus. In practice, performing such tests with controlled loading simulating the site condition is difficult so most of the tests have been performed in small scales which does not reflect the factual situation. Empirical models have been developed to predict the strength of rockfill utilizing available parameters but the reliability of them are not clear. These parameters influence the shear strength, and thus the friction angle (Ø). The shear strength of rockfill may vary directly with normal effective stress, dry density, particle roughness, particle crushing strength and inversely with grain size, uniformity of grading, and particle shape (Marsal, 1973). In a laboratory specimen, the maximum particle size (d) is determined according to the minimum dimension of the specimen (D). There are four different methods for preparing laboratory specimens; namely, parallel gradation technique, scalping method, quadratic gradation curve method and replacement technique (Varadarajan, 2003). The first two methods, commonly used by engineers, were adopted to investigate the effect of particle size on direct shear test. In the parallel gradation technique, the reduced particle-size laboratory specimens were formed with size distributions parallel to that of the original sampled material as it can be seen in Figure 1. In the scalping method, all particles considered oversize were removed (scalped) from the original material. Indeed, scalped gradation is considered for testing as equivalent grading instead of the original one. These techniques were used to determine the gradation of specimens in the tests and the numerical simulations related to the scale of shear boxes (Bagherzadeh, 2009). In both methods, a fraction of the representative gradation will be ignored which influences the shear strength characteristics of the base soil (Hamidi, 2012).

The maximum particle sizes of samples are being selected based on the dimension of the boxes according to ASTM-D3080. According to ASTM, the minimum specimen diameter for circular specimens, or width for square specimens, shall be 2.0 in. [50 mm], or not less than ten times the maximum particle size diameter, whichever is larger. The minimum initial specimen thickness shall be 0.5 in. [13 mm], but not less than six times the maximum particle diameter. The minimum specimen diameter to thickness or width to thickness ratio shall be 2:1. Jewell and Wroth (1987) suggested a ratio of shear box length to average particle size in the range of 50 to 300. According to Japanese standards, there are three approaches to determine the maximum allowable particle size for a large shear box test: a) 1/10–1/5 of the box length, (b) 1/7–1/5 of the box height, and (c) 1/9–1/5 of the smaller of the box length or height, among which the appropriate size is selected (Lee et al, 2009).

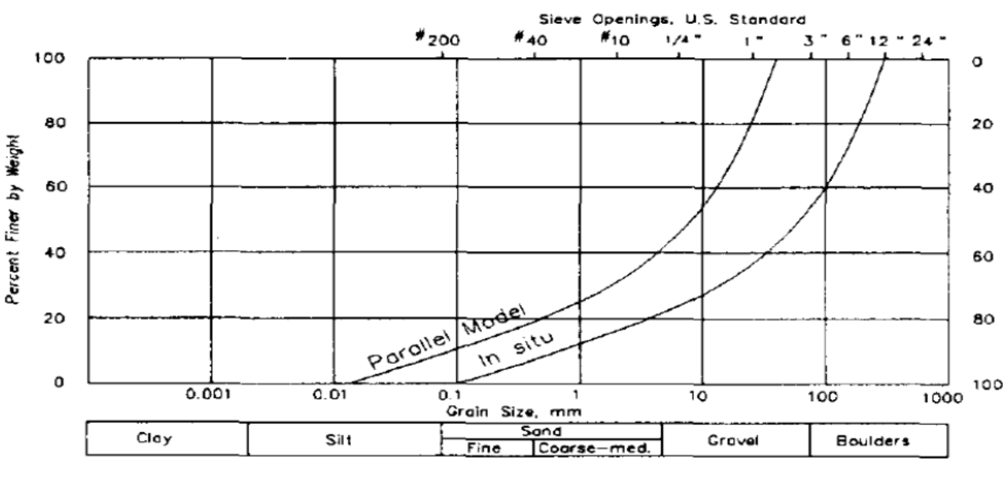

Figure 1: Parallel method illustrated with gradational analysis (Innacchione, 2000)

In the following parts, effective parameters for the determination of friction angle and shear strength have been described.

1. Parameters effecting shear strength of rockfill materials

1.1. Normal and Confining Pressure

Stress level affects the behavior of the rockfill material. Several authors have stated that the shear strength curve for rockfill is nonlinear, particularly at low confining pressures (triaxial: Marachi et al, 1969, Leps, 1970, and Indraratna et al.,1993). Therefore, in literature it is mentioned that a non-linear relationship should be applied for defining the failure envelope of this material. The increase of the normal stress reduces the peak friction angle (in decreasing rates) and the dilation angle. The rate of decrease diminishes as the normal stress becomes greater. This behavior can be explained as at very low confining stresses, the rockfill particles are relatively free to move with respect to each other and dilatancy effect can cause a significant increase in internal friction angle (Indraratna, 1994). The angle of dilation controls an amount of plastic volumetric strain developed during plastic shearing and is assumed constant during plastic yielding. As the confining stress increases, dilatancy effects gradually disappear due to particle crushing, causing a notable reduction of internal friction angle. This curved strength envelope of rockfill has a large impact on the stability analysis of rockfill dam due to the fact that a lower safety factor will be produced for the shallow slip surface when using constant friction angle (Indraratna, 1994; Barton and Kjaernsli, 1981).

The comparison of the materials' gradations before and after the tests shows that particle breakage occurs during the tests and the breakage amounts increases with increasing the normal stress. A number of correlations have been suggested to estimate the behavior of this material as well. Marachi et al (1969) carried out large scale triaxial tests on highly angular argillite, crushed basalt and rounded amphibolite and found that Ø does not appear to decrease significantly beyond $\sigma_n = 4.5$MPa. It should be noted that they did not perform tests beyond a confining pressure of 4.5MPa. Indraratna and his co-authors (Indraratna et al., 1993, 1998, Indraratna, 1994) performed tests on greywacke rockfill and basalt ballast. They found that the shear strength of the failure envelope was highly curved for confining stresses of less than 500kPa. Indraratna stated that the shear strength could be approximated by a linear Mohr-Coulomb criterion at stresses higher than 1.5MPa (as compared to the Marachi value of 4.5MPa above). Moreover, the comparison of the results of these tests with the results of the triaxial tests on the same material showed that the shear strength and peak friction angle from the direct shear tests were higher than those of the triaxial tests (Asadzadeh, 2009 and Lee et al 2009).

1.2. Water content and compaction

The water content, as the particles origin, has a double consequence. Initially, the increase of water content will affect the surface of particles where the condensation of water occurs. By affecting the surface of particles, it directly affects the inter-particle friction angle and in consequence a reduction in the shear strength can be obtained. The second consequence is related to the condensation of water in the particles micro-cracks, which influences the particles strength and facilitates the crushing. A trend was observed in the saturated specimens; however, wetting reduced the strength. The shear strength, peak friction angle, dilation angle, and particle breakage of the saturated specimens were less than those of the dry specimens. Performing similar tests in the dry-saturated tests shows that the strength parameters are less, but the particle breakage is more than those of the saturated tests. In these tests, also, saturation induced sudden settlement and shear stress reduction (Varadarajan et al 2006; Marsal, 1973).

1.3. Effect of Gradation

A number of researchers investigated the gradation effect on the shear strength by varying the coefficient of the uniformity (C_u) of rockfills. Marachi et al (1969) stated that a better graded rockfill, has a larger friction angle compared to uniform rockfill due to a better interlocking and less particle breakage in the former, the less breakage arises from the fact that in a well graded rockfill there are more inter-particle contacts and the load per contact is thus less than in a uniform rockfill. The impact of type of grading on the friction angle is about 2 to 3 degrees (Ghanbari et al., 2008).

1.4. Uniformity Coefficient

Generally, it could be expected that a poorly-graded rockfill (low uniformity coefficient, c_u), would have a higher strength than a well-graded rockfill assuming a constant void ratio for both. A well-graded material would be more likely to reduce the amount of dilation required due to the ‘gaps’ in the gravel matrix being filled with smaller particles. However, Marachi et al (1969) claim that if both rockfills were compacted to their maximum density then the well graded material could be expected to be stronger as it would have a greater density.

1.5. Maximum Particle Size

There is no common agreement on the effect of particle size on shear strength after evaluating the literature on this topic. Different views are presented with some indicating that the shear strength decreases with increasing particle size (Marachi et al., 1972; Marsal, 1973), while some have opposite views (Anagnosti & Popovic, 1982) or no effect at all (Charles & Watts, 1980). Some researchers have indicated that an increase in the particle size increases the load per particle, and hence crushing begins at a smaller confining stress, and causes a reduction in the friction angle; Barton (1981) showed that for materials compacted to the same density with geometrically similar grading, the smaller the elements are, the higher the friction angle of the material is. No effect at all has been observed by Charles & Watts, (1980). Marsal (1976) reports two triaxial tests each on rockfill-silt and rockfill-sand mixtures and compares these to a test on rockfill only. The clean rockfill and 10% sand-rockfill mixtures had Ø of 34.1° while the 30% sand-rockfill had a Ø of 39°. He attributes the difference to the lower initial void ratio in the 30% sand-rockfill mixture. The 10% silt-rockfill mixture showed a decrease in Ø to 28.8° while the 30% silt-rockfill mixture had the strength properties of the silt.

1.6. Influence of particles origin and shape

The nature of particles, such as shape and roughness have been studied by several authors (Marsal 1972, Marachi et al 1968). The particles origin concerns not only the mineralogic characteristics but also the extraction conditions, e.g., materials quarried from a mine, extracted by explosives, or extracted by backhoe, such as alluvial materials. The origin of a given material has a double mannered influence. First, the conditions of the particles surface affect the friction angle between particles, and second, the elastic and strength properties are dependent of the mineral characteristics. The mechanical characteristics of particles are then associated with the mechanical behavior of an equivalent continuum as a rockfill sample. Most researchers have focused on high quality rockfills. Kohgo et al (2007) supposed that rockfills with water absorption more than 10% are low quality materials and less than 3% is high quality material. Varadarajan et al (2006) showed that the angles of shearing resistance for quarried rockfill materials are higher than those for alluvial rockfill materials with comparable unconfined compressible strength of rockfill particles. Also, this angle for alluvial rockfill increases with the maximum particle size though the behavior of quarried rockfill material is the opposite. Nevertheless, this angle increases with the increase in unconfined compressive strength of alluvial rockfill particles. When breakage or crushing of particles happens, the grain-size distribution curve changes. In consequence the gradation curve measured at different stages of a test can reveal information about the amount of material crushed during the test. Nowadays, several constitutive models developed mainly on plasticity theory have incorporated the effect of particles' breakage, e.g., Salim and Indraratna (2004) and Kohgo et al. (2007). Kohgo's model is based on oedometric and triaxial tests conducted on two types of material (volcanic tuff and Andesite) tested both in dry and saturated state (Kohgo et al., 2007). He mentioned that breakage loads for particles of Tuff are strongly affected by the water content conditions but this effect for Andesite is small which may be due to difference in breakage characteristics of particles.

An angular rockfill may allow for stress concentrations that cause breakage of the particles at high confining pressures reducing dilation and leading to a lower overall rockfill strength than the rounded particles with less stress concentrations. The influence of grains' shape is an important factor for compacity, frictional and crushing characteristics. For frictional characteristics, the effect of grain's shape has been studied by Frossard (1979) who concluded that inter-particle friction angle seems to increase with angularity and that sphericity of particles has a notable effect on volumetric strains. As for compacity (i.e., the volume fraction that is filled), because during compaction the longer angular particles are more difficult to put in a dense arrangement than rounded regular particles. During loading stages, the flaws act as stress concentrators and will break easier than the rest of the particle. This will represent a higher deformability of the material. Due to the presence of flaws in angular particles and their breakage during loading, the angular materials can generate more finer particles than the non-angular materials. Some experimental results reported by Varadarajan et al. (2003) with alluvial (rounded) and quarried (angular) materials show strong differences between the behavior of both materials concerning shear resistance and deformation response. From discrete element analysis Nouguier-Lehon and Frossard (2005) showed that the angular particles dissipate less energy by rolling than rounded particles. This is explained by the restriction of rotations due to face to face contacts.

1.7. Density

It is generally accepted that the shear strength of rockfill increases with a higher relative density (Leps, 1970; Marsal, 1973). The effect of relative density on the friction angle can be explained by the phenomenon of interlocking the denser the rockfill; the greater the interlocking, a the greater the value of friction angle. The shape of the failure envelope is also affected by this factor. The dense rockfill specimens show a marked curvature on the stress -strain curve, with a distinct drop in the friction angle while the loose rockfill specimens shows minimal curvature and drop in friction because the loose material requires less dilation as particle have more freedom to move or rotate during shearing. The two curves tend to merge at very high confining pressures.

1.8. Influence of grain breakage

Factors like the size, shape and gradation of the particle are hardly analytically linked to the mechanical behavior of materials. Therefore, their association is made empirically, as the work of Barton and Kjaernsli (1981) who proposed as expression linking particle's size, shape and resistance to an equivalent friction angle of the media. The association made by Barton and Kjaernsli goes directly from particle's size and shape to the mechanical behavior in terms of friction angle. The approach taken here is relatively different. It is believed that factors such as particle's size, shape and gradation directly affect the breakage of particles, and then, breakage of particles affects the mechanical behavior of the rockfill materials. A detailed analysis of the influence of grain breakage on mechanical behavior of granular materials is the main subject of the next chapter. Table 1 presents a schematic correlation of the influence of different factors on breakage.

Table 1: Summary of factors affecting friction angle (Douglas, 2002).

Parameter	**Effect on ϕ while increasing parameter**	**Comments**
Effective normal stress (σ_n)	decrease	With high σ_n, ϕ is decreasing rapidly
Uniaxial compressive strength of rock	increase	More dilatancy, higher shear strength
Density	increase	More dilatancy, higher shear strength
Particle Size (D_{50})	decrease	
Ratio D_{max} /D_{50}	increase	
Angularity	increase	

2. Studies conducted by Direct Shear Test (DST)

Several investigators have tested shear resistance of rockfill using direct shear tests. Yamaguchi (2010) performed a shear box test on rockfill materials. In the test given under saturated conditions, the specimen was placed in a tank, fully immersed in water, as shown in Figure 1. He concluded that the large-scale box shear test can produce shear strength at a level similar to that of the large-scale triaxial compression test under the same normal stress (confining pressure), regardless of material type and whether the specimen is saturated or unsaturated, and can evaluate shear strength under a confining pressure lower than 49kPa, which is considered to be the verification limit of the large-scale compaction test.

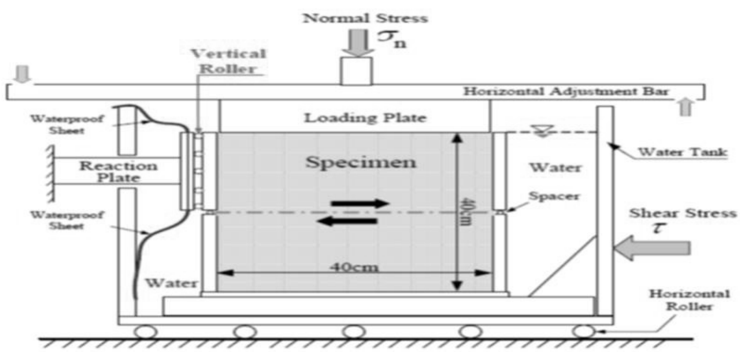

Figure 1: Schematic view of large scale shear box equipment (Yamaguchi, 2010).

Van der Linden, M. (2010) performed a shear test with medium scale box (Figure 2). In his tests, the density dependence of the rockfill is observed. Also, using Mohr- Coulomb's criterion, the obtained friction angles are in the range of 69° – 77° according to the test conditions, this would normally be around 50° (Indaratna, 1994) (Lee D. S., Kim, Oh, & Jeong, 2008). Lee et al (2009) mentioned that the obtained friction angles in his tests range from 39 to 49 degrees according to test conditions, with an average of 43.6^0. The larger values occur with greater density, smaller particle size, and air-dried samples, as recorded in previous studies based on large triaxial tests. Van der Linden justified that these values were due to wide range caused by the small range of normal stress applied and the few number of tests conducted. An increase in friction angle with an increase in density was seen. Dependency of the particle size on the friction angle is not clearly observed, due to the fact that there were only different fractions tested.

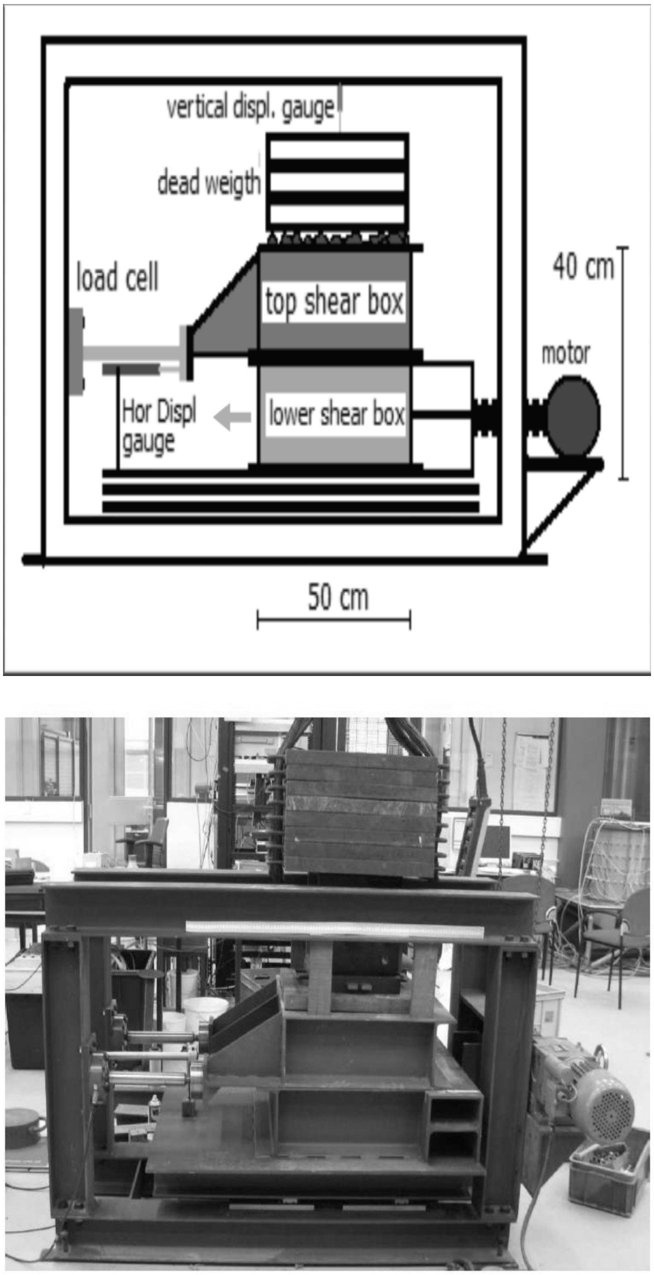

Figure 3: The direct shear box used, the orange arrow indicates the direction of shearing (Van der linden 2010).

Specimen size or scale effects were studied as early as 1936. Parsons presented test results for crushed quartz and for Ottawa uniform sand which showed that larger shear boxes produced lower values of friction angle (Moayed, 2012). Tests were done with very small, normal stresses to obtain the failure envelopes (0.015 to 0.1 kg/cm^2 or 1.5 to 9.8 kPa) that such low, normal stresses in conventional direct shear machines would be unlikely. Palmeira and Milligan's (1989) test results using three different size shear boxes showed shear zone thickness at the mid-height of sample was significantly affected by the scale factor (Moayed, 2012). The term "shear zone" means the small layer that is involved in the shearing process and the area where mechanism of localization occurs and this zone consists of many shear bands propagate from the edges of the shear box. Cerato and Luteneger (2006) performed DST using three different sizes of boxes (60 x 60 mm; 101.6 x 101.6 mm, and; 304.8 x 304.8 mm). In their study, they reported decrease in the friction angles with an increase of the shear box. They also studied the scale ratio of the specimen: height to diameter ratio (H/D) and width to maximum particle size ratio (W/D_{max}). They reported an increase of the friction angle with a decrease of the H/D ratio. Moreover, in literature it is often mentioned that square boxes are being used more frequently than circular boxes because circular boxes generate more problems during testing since the displacement sensors have to be placed more carefully (Ramírez Oyanguren et al, 2008).

Nakao and Fityus (2009) performed several large scale direct shear tests to study the factors that have an effect on the measured effective internal friction angle and to examine the effects of factors such as applied normal stress and shearing rate. Besides, to examine what effect the scale of the test has on the measured effective friction angle. The dimension of used shear box was 300 mm × 300 mm ×190 mm. Before testing commenced, the bulk sample was screened to remove all particles greater than 19 mm (about 10 % of the raw sample). The shearing rates were carried out at 7.06, 0.63, and 0.05 mm/min.

They concluded that shearing rate of around 7 mm/min is too fast to ensure fully drained (and hence maximum effective friction) behavior to be determined for the tested material using the large shear box. A shearing rate of around ten times slower would seem to give significantly higher effective friction angle values, but 100 times slower will give similar or even slightly reduced values. The results obtained here demonstrate that small shear box tests are no substitute for large shear box tests, and that downsizing the grading and the size of the sample tested will cause the effective friction angle to be under-estimated by as much as 4°. Moreover, Nakao and Fityus mentioned that shortcuts including testing a sample of reduced size in a small box, shearing the sample too quickly, and testing the same sample more than once in the testing of coarse granular materials will lead to significant differences in the measured results, that in most cases, are more conservative than the results obtained by adhering to the correct procedure.

REFERENCES

[1] Anagnosti, P. & Popovic, M., 1982. Evaluation of shear strength for coarse-grained granular materials. In Fouteenth Congres on Large Dams. Rio de Janeiro, 1982. ICOLD.

[2] Asadzadeh M., “Direct shear testing on rockfill material”. Arabian journal for science and engineering, vol 34, number 2B October, pp 379-396, (2009).

[3] ASTM D3080/D3080M – 11, “Direct Shear Test of Soils Under Consolidated Drained Conditions”, (2004).

[4] Bagherzadeh A., “Numerical and experimental direct shear tests for coarse grained soils”. Journal of Particuology, vol. 7, no. 1, pp. 83-91, (2009).

[5] Barton, N., and Kjanernsli., “Shear strength of rockfill”. Journal of the Geotechnical Engineering Division, Vol. 107, No. 7, July 1981, pp. 873-891, (1981).

[6] Barton, N.R. “Review of a new shear strength criterion for rock joints”. *Engineering Geology*, vol. 7, issue 4, pp. 287-332, (1973).

[7] Barton, N.R. “The shear strength of rock and rock joints”. International Journal for Rock Mechanics, Mining Sciences and Geomechanical Abstracts, vol.13, No.9, pp. 255-279, (1976).

[8] Cerato, A.B. & Lutenegger, A.J.,” Specimen size and scale effects of direct shear box tests of sands”. Geotechnical Testing Journal, 29(6), pp.1-10, (2006).

[9] Cetin H. et al., “Settlement and slaking problems in the world’s fourth largest rock-fill dam, the Ataturk Dam in Turkey”. Engineering Geology, vol.56. pp. 225–242, (2000).

[10] Charles J.A., “The engineering behaviour of fill materials: the use, misuse and disuse of case histories”. Geotechnique 58, No. 7, 541–570, (2008).

[11] Charles, J.A. & Watts, S.K. The influence of confining pressure on the shear strength of compacted rockfill, Geotechnique, 30(4), pp.353-67, (1980).

[12] Frossard E. et al. “Rockfill shear strength evaluation: a rational method based on size effects”. Ge´otechnique 62, No. 5, 415–427, (2012).

[13] Ghanbari A. et al., “An Experimental Study on the Behavior of Rockfill Materials Using Large Scale Tests”. Electronic Journal of Geotechnical Engineering, Vol. 13, Bundle G, (2008).

[14] Hamidi A., “Impact of gradation on the shear strength-dilation behavior of well graded sand-gravel mixtures”. Scientia Iranica, Volume 19, Issue 3, June 2012, pp. 393–402, (2012).

[15] Innachione A.T, Vallejo L.E., “Shear strength evaluation of clay- rock mixtures”. Book Chapter TA - Slope Stability 2000, (2000).

[16] Indraratna, B., “The effect of normal stress -friction angle relationship on the stability analysis of a rockfill dam”. Geotechnical and Geological Engineering, 12, pp.113- 21, (1994).

[17] Indraratna, B., Ionescu, D. and Christie, H.D. “Shear behaviour of railway ballast based on large-scale triaxial tests”.Journal of Geotechnical and Geoenvironmental Engineering, vol.124 (5), pp. 439-449, (1998).

[18] Indraratna, B., Wijewardena, L.S.S. and Balasubramaniam, A.S. “Large-scale triaxial testing of greywacke rockfill”. *Geotechnique*, 43 (1), pp. 37-51, (1993).

[19] Jewell, R. A. and Wroth, C. P., “Direct Shear Tests on Reinforced Sand”. Geotechnique, Vol. 37, No. 1, pp. 53–68, (1987).

[20] Kohgo, Y., I. Asano, and Y. Hayashida. ” Mechanical properties of unsatured low quality rockfills. Soils and Foundations 47(5), 947–959, (2007).

[21] Lee, D.S., Kim, K.Y., Oh, G.D. & Jeong, S.S, “Shear characteristics of coarse aggregates sourced from quarries”. International Journal of Rock Mechanics & Mining Sciences, 46, pp.210-18, (2008).

[22] Leps, T.”Review of shearing strength of rockfill”. Journal of the Soils Mechanics and Foundations Division. ASCE 96(SM4), 1159–1170, (1970).

[23] Marachi, D.N., Chan, C.K. & Seed, B.H., “Evaluation of properties of rockfill materials”. Journal of the Soil Mechanics and Foundations Division, 98(SM1), pp.95-114, (1972).

[24] Marsal, R.J. “Large scale testing of rockfill materials”. Journal of the Soil Mechanics and Foundations Division Proceedings of the American Society of Civil Engineers, vol.93 (SM2), pp. 27-43, (1976).

[25] Marsal, R.J. “Mechanical properties of rockfill”. In Embankment Dam Engineering Journal. Willey & Sons, N.Y., pp. 109-201, (1973).

[26] Moayed R.Z, Alizadeh A., “Effects of shear box size on the strength for different type of silty sands in direct shear tests”. 5th Asia-Pacific Conference on Unsaturated Soils 2012, Volume 1, 2012, pp. 248-254, (2012).

[27] Nakao, T., Fityus, S., “Direct Shear Testing of a Marginal Material Using a Large Shear Box”. Geotechnical Testing Journal, Vol. 31, No. 5, (2008).

[28] Palmeira, E.M. and Milligan, G.W.E.,” Scale effects in direct shear tests on sand”. In Proceedings from the 12th. International Conference on Soil Mechanics and Foundation Engineering, Balkema, Rotterdam, 1, pp. 739-742, (1989).

[29] Ramírez Oyanguren, et al, “Stability analysis of Llerin Rockfill Dam: An in situ direct shear test”. Engineering Geology No.100, pp.120–130. (2008).

[30] Salim, W. and B. Indraratna. ” A new elastoplastic constitutive model for coarse granular aggregates incorporating particle breakage. Canadian Geotechnical Journal 41(4), 657–671, (2004).

[31] Van der Linden, M., “Determine shear strength of Bremanger aggregate at low normal stress using medium size direct shear box tests”. BSc. Thesis. TU Delft, (2010).

[32] Varadarajan A., “Testing and Modeling Two Rockfill Materials”. Journal of Geotechnical and Geoenvironmental engineering, vol 129, issue 3, pp. 206–218, (2003).

[33] Varadarajan A. et.al., “The role of nature of particles on the behavior of rockfill materials**”**. Journal of soils and foundations, vol 46, issue 5, pp. 569-584, (2006).

[34] Yamaguchi,Y, “Strength evaluation of rockfill materials considering confining pressure dependency”. The 1st International Symposium on Rockfill Dams, (p.10). Minamihara, (2010).