Direct Shear Testing of Rockfill Material

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Abstract

The shear strength of granular materials is mainly derived from the particle sliding friction and resistance resulting from reorientation and sample dilatancy. Parameters affecting the shear strength therefore depend on the relative density, gradation, particle strength, particle size and shape, and degree of saturation of the specimen. In this study a customized shear box is fabricated and used to perform direct shear tests of large diameter gravels. The effects of particle size, gradation, shearing rate and moisture on shear strength are investigated. Sample dilatancy is observed during shearing for all specimens. The internal friction angle increases with the increase of particle size and shearing rate; shear strength peaks with a sand and gravel mixture weight ratio of 0.6; the existence of moisture reduces the shear strength. The 6.3mm sample is sheared under a wide normal pressure range from 2kPa to 600kPa indicating a progressive flattening failure envelope.

Introduction

The shearing strength of granular soils such as sand, gravel and rockfill has been a subject of interest among civil engineers for many years. A large amount of tests including direct shear tests and triaxial tests have been performed to investigate the shearing strength of granular soils.

Duncan (2004) summarized all the factors affecting the internal friction angle of sand, gravel and rockfill based on a thorough evaluation of the available published data. These factors are relative density, gradation, particle strength, particle shape and degree of saturation. High relative density, good gradation, strong particles and angular particles result in high internal friction angles.

Rowe (1962) concluded that there were three components of the shear strength of granular materials: (1) strength mobilized by frictional resistance (ϕ_u); (2) strength developed by energy required to rearrange and reorient soil particles (ϕ_r); and (3) strength developed by energy required to cause expansion or dilation of the

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material (ϕ_d). Lee, seed and Dunlop (1967) pointed out that particle breakage should be also included in internal friction angle. However, it is difficult to separate the contribution to internal friction angle made by particle breakage and reorientation. They recommended that both these processes were considered together in ϕ_r.

In this study three samples were tested. The tested particle sizes are from 2.0mm to 9.4mm. Particle size, shearing rate, gradation and moisture effect on the shear strength of gravels were studied.

Test setup

Testing materials-gravels. The original sample was dried in the oven for at least 12 hours before the testing program was initiated thus the moisture content was essentially zero. Grain size analysis was performed by sieve analysis. Sieves with opening size of 9.42mm, 6.30mm, 4.76mm and 2.00mm were used to sieve the rocks. Gravels retained on sieves with opening size of 6.30mm, 4.76mm and 2.00mm were used in this study and tested in the direct shear-testing program. Figure 1 shows a small sampling of the rock particles tested after sieve analysis. The grain size distribution of the testing material is shown in Figure 2.

Testing protocol. Three groups of test gravel specimens were used during this study which are: Group 1 with particle diameters of 6.3mm to 9.4mm; Group 2 with particle diameters of 4.8mm to 6.3mm; and Group 3 with particle diameters of 2.0mm to 4.8mm. Group 1 was sheared at two speeds (fast and slow at 1mm/min and 3.0mm/min respectively) under normal load from 20N (2kPa) to 6000N (600kPa). Groups 2 and 3 were sheared at 1 mm/min under normal load 200N (20kPa), 1000N (100kPa) and 3000N (300kPa). Group 3 was also tested with fine sand or water at 1mm/min under 1000N (100kPa).

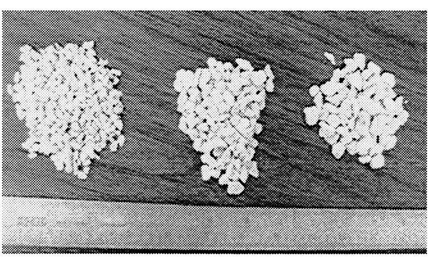


Figure1. Photo of testing samples

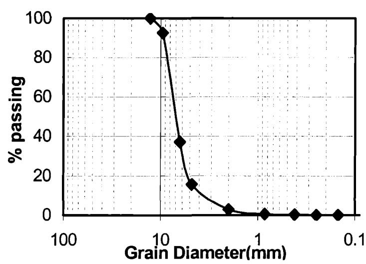


Figure 2. Grain size distribution of rock specimen

At the start of each test, a light coating of grease was applied between the halves of shear box to reduce friction between the top and bottom halves of the shear box during testing. The number of the particles in each specimen was counted during placement into the shear box, which were approximately 1200 particles for specimen of Group 1. Rocks were poured into the shear box in four lifts and each lift was tamped by a wooden rod with ten taps in order to minimize the effects of sample preparation among the various tests. Figure 3 shows a schematic diagram of the rock placement in the shear box.

Once the shear box was filled, the specimen height and weight was measured and the specimen was ready for testing. During each test cycle, the desired vertical (normal) load was applied to the specimen. After the vertical deformation stabilized, the alignment screws were removed from the shear box and a gap with approximately 1mm between the shear box haves was opened using gap screws. Then specimen was sheared at a prescribed shear rate. During the test, the vertical deformation, shear load and shear displacement were all recorded as a function of time. Normal load was also recorded as a function of shear displacement.

Direct shear apparatus. The dimensions of the customized shear box needed for this study was dictated by the specimen and particle sizes to be tested. Based on a review of the literature (Holtz and Gibbs, 1956; ASTM D 3080-98), the preferable dimensions of a direct shear specimen, and hence the box, were: $D_{specimen}=10\times D_{particle}$, $H_{specimen}=6\times D_{particle}$, $D_{specimen}>2\times H_{specimen}$.

In this study, the granular material tested was uniformly distributed rock, with the maximum particle diameter of 9.4mm. Thus the minimum dimension of shear box needed was 100mm×100mm×54mm.

The direct shear testing apparatus used was a S2215A Digital Direct-Residual Shear Apparatus manufactured by GEOTEST Instrument Corp. (Figure 4). A data acquisition system was developed to measure and record a number of parameters such as: shear and normal loads, the vertical and horizontal displacements. The software could generate diagrams of specimen consolidation and shearing.

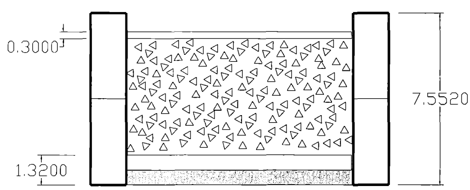


Figure 3. Rock particles in the shear box (dimensions in mm)

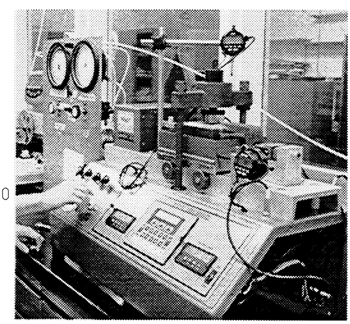


Figure 4. Photo of Direct Shear apparatus used in testing

Direct shear tests

Each test was repeated three times to study the effects of testing repeatability. The test results are shown in Figure 5(a). It shows that the performed tests were fairly consistent. Table 1 summarizes the entire set of tests performed. Normal loads below 1000N (100kPa) were applied with the valve on low load range and normal loads above 1000 N with the valve on the high load range. By doing so, the deformation effect of the loading frame was minimized since the load cell moves in the low load range and whole loading frame moves in the high load range.

The real applied normal load was measured in the direct shear tests. It was observed that the normal load increased particularly when the sample started to dilate.

The increase of normal load resulted from resistance of loading frame occurred when the sample dilated. An example in Figure 5(b) shows the changes of normal load during shearing.

The vertical deformation can decrease or increase during shearing depending the stress levels. Figure 6(b) shows the vertical deformation of gravels with particle size from 6.3mm to 9.4mm at 1mm/min shearing rate. Even loose samples dilated, which was different from the observed behavior of the sand specimens. It is found in Figure 6(b) that sample has large vertical deformation and small contraction at low normal load. The sample is easy to contract and hard to dilate at high normal pressure.

Table 1. Summary of performed tests

Soil sample	Preset normal stress (kPa)	Normal stress at peak shear stress (kPa)	Maximum shear stress(kPa)	Shearing rate (mm/min)	Internal friction Angle(°)
1A:(6.3~9.42 mm)	2.0,9.0/10.0, 20.0,50.0,100.0,300.0, 600.0	5.0,12.0/13.0,24.0,5.0,122.0,325.8, 625.0	12.9,23.7/23.5,44.0, 89.8,165.8,439.8,734.9	1	57.1/ 49.5
1B:(6.3~9.42mm)	2.0,9.0/20.0,100.0,300.0	5.0,12.0/23.0,127.0,331.0	12.0,25.8/48.5,197.1,435.3	3.8/3	63.1/ 51.2
2:(4.76~6.30 mm)	20.0,100.0, 300.0	23.0,115.4, 319.1	39.1,166.3, 381.5	1	48.7
3:(2.00~4.76 mm)	20.0,100.0, 300.0	24,107.7, 308.5	31.3,121.3, 302.4	1	43.3
Gravel with sand or water	100.0	N.A.	90.2,119.6,152.7,124.8,121.3,113.66	1	N.A.

Note: "/" used in the second, third and forth column to separate stresses to two groups, i.e. low pressure and high pressure.

The existence of sand and moisture can change the shear strength of gravels. Gravels with sand mixtures of different weight ratios were sheared at the same condition to show the effect of sand. A moisturized sample was also sheared. Those test results were plotted on one Figure 6 (a) with sand only and gravel only sample.

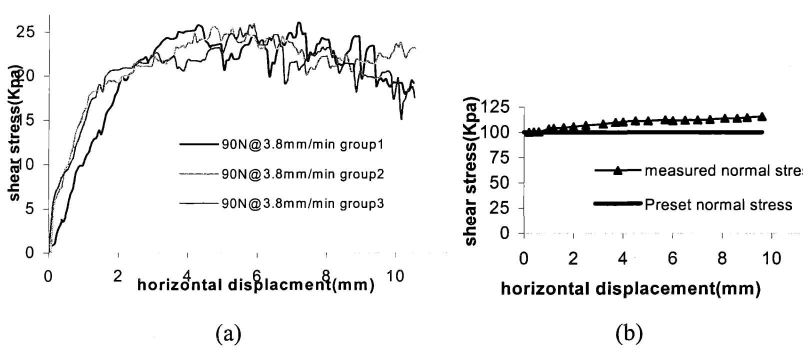
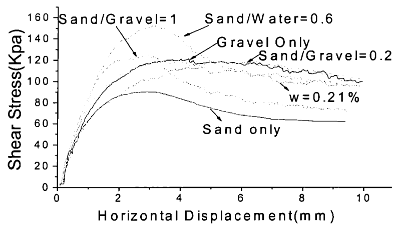


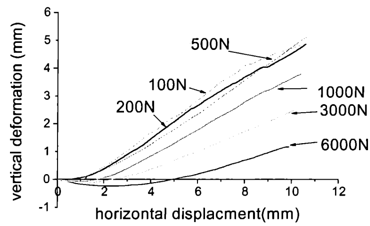
Figure 5. (a) Shear stress vs. horizontal displacement (b) Normal stress vs. horizontal displacement of one test under 100kPa normal stress

Internal friction angle

The internal friction angles of gravels under different conditions were calculated from the slope of linear fit line. The calculated internal angle is shown in Table 1. In the table "57.1/ 49.5" represents the internal friction derived under 2.0kPa and 9.0kPa is 57.1° and the internal friction angle derived under 10.0kPa, 20.0kPa, 50.0kPa, 100.0kPa, 300.0kPa, 600.0kPa is 49.5°.



(a)



(b)

Figure 6. (a) Shear behavior of gravel and sand mixture or moisturized gravels under 1000N (ratios are weight ratio) (b) vertical deformation

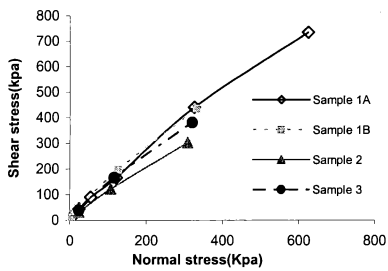


Figure 7. Mohr diagram of testing gravels

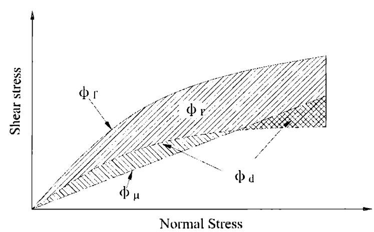


Figure 8. Variation of components of ϕ_f with normal stress in sand (after Lee, Seed and Dunlop, 1967)

Shear strength characteristics of gravels

Effects of different factors on shear strength. Under low normal load (20kPa and 100kPa) the shear strength increased with high shear rate (Table 1). But under high normal load (300kPa) shearing rate showed a small effect on the shear strength. Gravels with larger size particles produced higher internal friction angle. Gravels with large size particles developed high shear strength. Particularly under high normal load (300kPa) particle size showed an obvious effect on the shear strength of gravels. From results of internal friction angles, it was clear that higher shearing rate resulted in higher internal friction angle.

Sand and water were added to gravel to study their effects on the shear strength. Although only a limited numbers of tests (Figure 6(a)) were performed, they still indicated the trends of effect. Figure 6(a) shows that gravels with 2% moisture content had slight lower shear strength than the dry gravels. One explanation is that water can lubricate gravels to reduce the sliding friction between particles; therefore, the peak shear stress was lower.

Gravel with sand mixture with sand to gravel weight ratio of 0.6 developed the maximum shear strength. The shear behavior of sand and gravel mixture with ratio of 0.2 was almost exactly the same as pure gravels. By adding the same weight of sand it did not change the max shear strength of gravels much. It reached the peak earlier and had low shear residue strength. In the mixture of sand to gravels ratio 0.6 resulted in a much higher shear strength.

Nonlinear failure envelope under high normal pressure. The test results of sample with 6.3 mm minimum diameter at 1mm/min shearing rate of Figure 7 indicate a curved Mohr-Coulomb failure envelope. The slope of the failure envelope decreased with the increase of normal stress. This decrease is particularly obvious under high normal stress. To understand the behavior of friction angle at failure (ϕ_f), it is helpful to look at the influence of stress level on its components (Yapa, 1995). The sliding friction ϕ_u was generally constant within a reasonably large stress range. This is shown schematically as a straight line in the $\tau - \sigma$ plot in Figure 8. At a given void ratio the dilantancy component varied greatly with stress level; ϕ_d decreased with the increase of confining pressure, and may even become negative under high confinement. At high stress levels both particle reorientation and breakage absorbed greater amount of energy increase ϕ_r. However, the total internal friction angle ϕ_f usually decreased under increasing stress levels because the increase in ϕ_r was less than the decrease in ϕ_d at all stress levels. This resulted in a curved failure envelope followed that of Figure 8.

Conclusions

The findings of this study are summarized as follows. The internal friction angle increased with the increase of shearing rate. Gravels of large particles had higher internal friction angles. Under high normal load, a larger shear displacement was needed to reach peak shear stress. The failure envelope of direct shear testing results was curved with a progressive flattening. Gravel samples dilated in the process of shearing. At high normal load, there was sample contraction at the beginning of shearing and then dilatancy. Direct shear testing results of specimens with sand and gravel mixture indicated that the ratio of sand to gravel affected shear strength of the mixture. The mixture with a weight ratio of 0.6 had the maximum shear strength. The existence of water in gravels reduced shear strength.

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