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Shear strength assessment of a well-graded clean sand

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ABSTRACT

Shear strength of soil depends on various factors including the grain size distribution, stress level and the moisture content of the soil. This paper presents an investigation of the shear strength of a well-graded clean sand using direct shear tests. Tests are performed with varying normal stresses from 12.5 kPa to 400 kPa and varying moisture contents from 0 to 6%. A total of 80 direct shear tests are conducted which showed that the peak friction angle is influenced by normal stress levels and the moisture contents of the samples. The peak shear stress to normal stress ratio is higher at lower normal stress, which decreases with the increase of stress levels. The decrease of the stress ratio is higher for the moist sands than the dry sands. The dry unit weight of the sand is generally decreased with the increase of moisture content, which may contribute to the reduction of the friction angle for moist sands. The rate of shear displacement is varied to examine the effects on the shearing response of the sand. The shearing response of the sand is not found to depend significantly on the rate of shearing displacement within the range investigated.

RÉSUMÉ

La résistance au cisaillement du sol dépend de divers facteurs, y compris la distribution granulométrique, le niveau de stress et la teneur en humidité du sol. Cet article présente une étude de la résistance au cisaillement d'un sable propre bien gradué à l'aide de tests de cisaillement direct. Les essais sont effectués avec des contraintes normales variant de 12,5 kPa à 400 kPa et des teneurs en humidité variant de 0 à 6%. On a effectué un total de 80 essais de cisaillement direct qui ont montré que l'angle de frottement maximal est influencé par les niveaux normaux de contrainte et le contenu en humidité de l'échantillon. La contrainte de cisaillement maximale au rapport de contrainte normale est plus élevée à une contrainte normale inférieure, ce qui diminue avec l'augmentation des niveaux de stress. La diminution du rapport de contrainte est plus élevée pour les sables humides que pour les sables secs. Le poids unitaire sec du sable est généralement diminué avec l'augmentation de la teneur en humidité, ce qui peut contribuer à la réduction de l'angle de frottement pour les sables humides. Le taux de déplacement du cisaillement est varié pour examiner les effets sur la réponse de cisaillement du sable. On ne trouve pas que la réponse de cisaillement du sable dépend significativement de la vitesse de déplacement du cisaillement dans la plage étudiée.

1 INTRODUCTION

The shear strength of cohesionless material (sand) is generally expressed in term of the angle of internal friction. It is achieved from the rolling and sliding frictions between grains and particle interlocking. Particle interlocking offers resistance against volume expansions (dilation) in dense sand (Duncan et al. 2014; Terzaghi et al. 1996).

Density is one of the key factors which increases shear strength by increasing interparticle contacts. The density is a variable property of soil that changes with compaction and moisture content (Duncan et al. 2014; Terzaghi et al. 1996). Taylor (1948) revealed through a series of direct shear tests on standard Ottawa sand with variable void ratios that the angle of internal friction decreases with the increase in void ratio and decrease in density. Wei et al. (2018) showed that the ratio of shear stress to normal stress decreases gradually with the increase in moisture content up to 8% for a soil-rock mixture. It was also evident that strain hardening is more significant than strain softening at higher moisture contents (Wei et al. 2018).

On the other hand, confining pressure or normal stress in the direct shear test has a significant influence on the shear strength of soil. The increase in confining pressure reduces interparticle friction coefficient due to the breakage of particles at contacts and polishing of particle surfaces with the increase of interparticle contact forces. As a result, the shear resistance from the interparticle sliding and rolling friction is reduced (Duncan et al. 2014; Terzaghi et al. 1996). A same type of observation was also reported in Wei et al. (2018) from the direct shear tests on the soil-rock mixture. A reduction in stress ratio, as well as a reduction of dilation, was observed with the increase in confining pressure (Charles and Watts 1981; Marschi et al. 1969). However, at low confining pressure, the shear strength can be less due to high initial void ratio.

The shear strength of soil was also found to depend on the rate of loading. A study showed that the angle of internal friction of uniform dense Cambria sand increases about 4.7° with changing of strain rate from 0.0042 %/min to 0.74 %/min in an undrained triaxial test (Yamamuro and Lade 1993). A similar effect of strain rate was found in drained triaxial compression tests of crushed coral sand (Lade and Nam 2009). However, no significant effect was observed on Hostun and Toyura sand (Matsushita et al. 1999). Wei et al. (2018) conducted a study on soil-rock mixture with 4 shear displacement rates (2, 5, 10, 20 mm/min) and four normal stresses (100, 200, 400 & 800 kPa) and found that there is a greater rate of increase in stress ratio with the increase in shear displacement rate for lower normal stresses where maximum change in stress ratio was 0.3. Beyond the rate of 10 mm/min, the change in stress ratio became negligible (Wei et al. 2018). The inertia of the material plays a role at a very high strain rate and there can be a change in the material response due to strain rate change (Abrantes and Yamamuro 2002; Matsushita et al. 1999).

The purpose of this study is to examine the shear strength of a well-graded clean sand considering the effect of density, moisture content, normal stress, and shear displacement rate. A series of direct shear tests are conducted with soil samples having various moisture contents and densities.

2 TEST MATERIAL

The grain size distribution of the well-graded clean sand used in this study is shown in Figure 1. It has a mean particle size (D_{50}) of 0.742 mm, coefficient of uniformity (C_u) of 5.81, coefficient of curvature (C_c) of 2.04, fines content of 1.3% and gravel content of 0.87%. The particles retained on #4 sieve (i.e., the gravel) are removed from the samples to comply with the requirement of direct shear box size relative to the maximum particle size according to the ASTM D3080 standard.

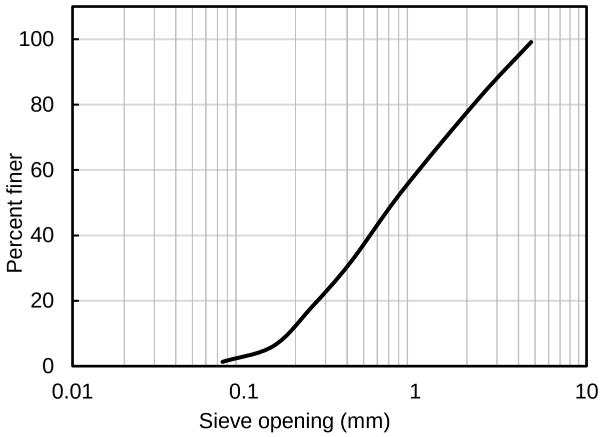

Figure 1. Grain size distribution of test material

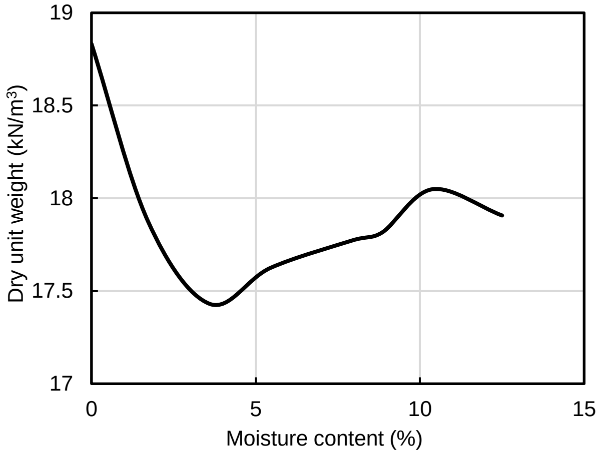

Figure 2. Standard Proctor compaction test results

The results of the standard Proctor compaction test conducted on a sand sample are shown in Figure 2. It is noted that the dry unit of the sand is the highest at 0% moisture that reduces with the increase of moisture content. Beyond 4%, the dry unit weight increases with the further increase of moisture content and after 10 %, the curve moves to the wet side of the compaction curve. The reduction of dry unit weight at lower moisture contents may be due to capillary tension effect suppressing the lubrication effect, which encloses the air inside the film of water leading to the decrease in the dry unit weight (Das 2010). The maximum dry unit weight of the sand sample is obtained as 19.3 kN/m^3 after compacting a dry sand sample by 50 blows of standard Proctor hammer in standard Proctor mold and vibrating it under surcharge of 5 kg.

Table 1. Direct shear test program of well-graded clean sand

Test No	**Moisture Content (%)**	**Compaction**	**Dry Unit Weight (kN/m^3)**	**Shear Displacement Rate (mm/min)**	**Normal stress (kPa)**
1-6	0	Yes	18.95	1	12.5, 25, 50, 100, 200, & 400
7-12	1.5		17.39		
13-18	3		16.98		
19-24	6		17.23		
25-30	0	No	16.13		
31-36	1.5		12.67		
37-42	3		11.60		
43-48	6		11.49		
49-52	0	Yes	19.05	0.25	50, 100, 200, & 400
53-56				0.5	
57-60				1	
61-64				1.5	
65-68		No	16.20	0.25	
69-72				0.5	
73-76				1	
77-80				1.5	

3 TEST METHOD

The direct shear test apparatus at Memorial University geotechnical laboratory was used in this test program. The shear box has 63.5 mm diameter and allows a specimen thickness of 26 mm. The test facility has a capacity of applying normal loads from 50 N to 6400 N, shear displacement of up to 20.32 mm, and shear displacement rate from 0.0025 mm/min to 7.62 mm/min. Sand samples were prepared by compacting the poured sample with 25 blows of free fall temping rod inside the shear box in three layers. After compacting, the volume and mass of the sand sample used in the shear box were measured to determine the unit weight. The moist samples were prepared by placing the sand in the shear box immediately after uniform mixing of the sand with predetermined amounts of moistures. The moist sand sample in the shear box was placed in the same way as the dry sample. After completion of each test, the actual moisture content of each sample was determined through oven-drying. Samples were also prepared without compaction in both dry and moist conditions. Shear displacement rate of 1 mm/min was applied in the first 48 direct shear tests. Three other displacement rates were applied in the dry samples to examine the strain rate effects. Details of the test program are shown in Table 1.

4 TEST RESULTS

First 48 tests are used for the characterization of the effects of confining pressure, dry unit weight, and moisture content on the shear strength. The stress–strain response, peak stress ratio and angle of internal friction are examined. The remaining 32 tests are used in exploring the effect of shear displacement rate on the shear strength.

4.1 Stress–Strain Responses

Each sand sample was tested at six normal stresses. For each normal stress, the shear stresses against the shear displacements are examined. Shear stress is represented as a ‘stress ratio’ defined as the ratio of the shear stress to the normal stress. The volumetric strain is examined in term of a dilation rate, defined as the ratio of the vertical displacement rate (dv) to the horizontal displacement rate (du) (i.e., Dilation rate $=\frac{dv}{du}$), after Simoni and Houlsby (2006).

Figure 3 shows the changes in stress ratio with horizontal displacement for the compacted samples for different normal stresses. In the figure, the peak stress ratio is the highest for 12.5 kPa of normal stress that reduces with the increase of the normal stress. The reduction of peak stress ratio with the increase in normal stress is more for the moist samples than for the dry samples. The peak stress ratio is reduced from 1.2 to 1.1 for increasing of normal stress from 12.5 kPa to 400 kPa for dry samples whereas for the moist samples, the peak stress ratio is reduced from 1.6 to 0.7 (Figure 3(d)), showing the effect of the moisture contents. It is also to be noted that post–peak degradation of the stress ratio is significant for the dry sand. Tarhouni et al. (2017) demonstrated similar peak and post–peak behavior for dense silica sand. For the dry sand samples, the stress ratio is reduced from the peak value of around 1.2 to the critical state value of around 0.6–0.8. The peak stress ratio is obtained at 1–1.2 mm horizontal displacement for lower normal stresses (12.5 & 50 kPa) whereas it is obtained at the higher horizontal displacement of 1.5–2.5 mm for higher normal stresses (200 & 400 kPa). However, there is no significant post–peak degradation in the moist samples. Similar behavior was observed for dry and moist sands earlier by the authors (Saha et al. 2019). The stress ratio becomes nearly constant after reaching peak stress ratio at around 1–1.5 mm of horizontal displacement for the moist samples. Wei et al. (2018) also showed that the post–peak degradation of stress ratio for the compacted soil–rock mixtures with higher moisture is less significant.

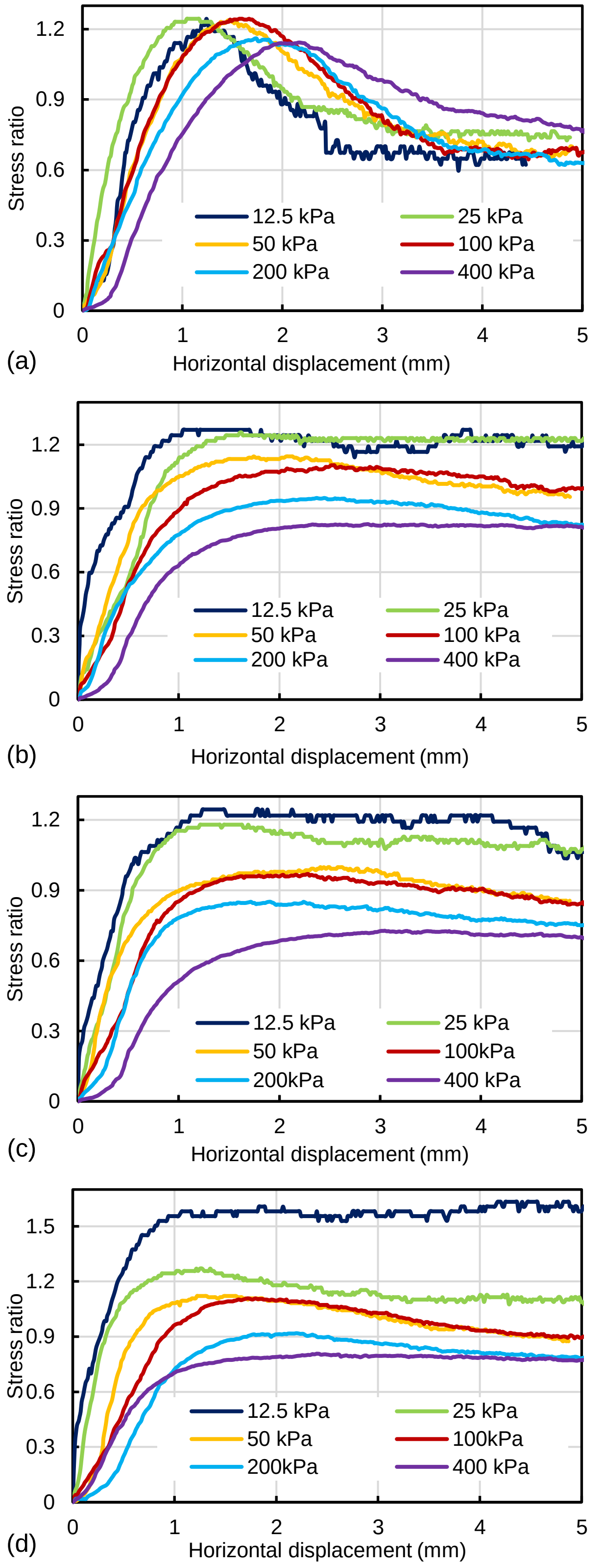

Figure 3. Stress ratio for compacted sand sample for varying moisture contents a) 0% (Dry), b) 1.5%, c) 3%, and d) 6%.

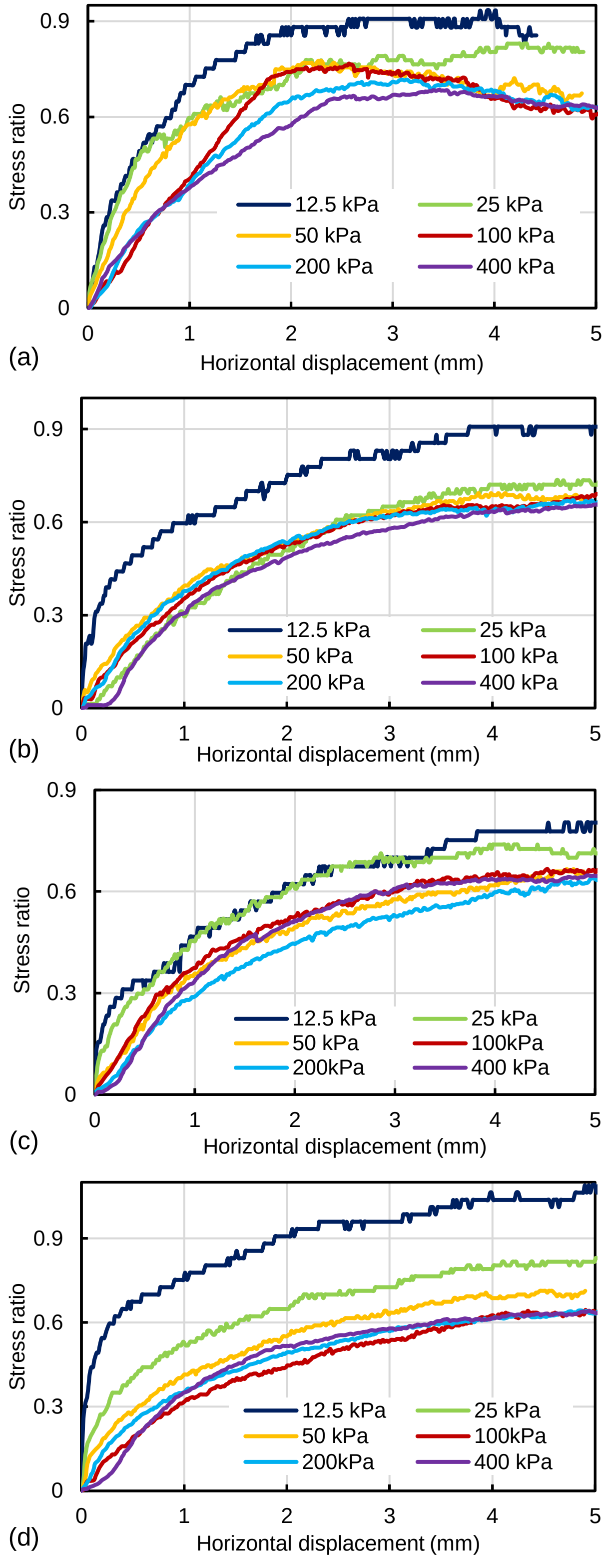

Figure 4. Stress ratio for uncompacted sand sample for varying moisture contents a) 0% (Dry), b) 1.5%, c) 3%, and d) 6%.

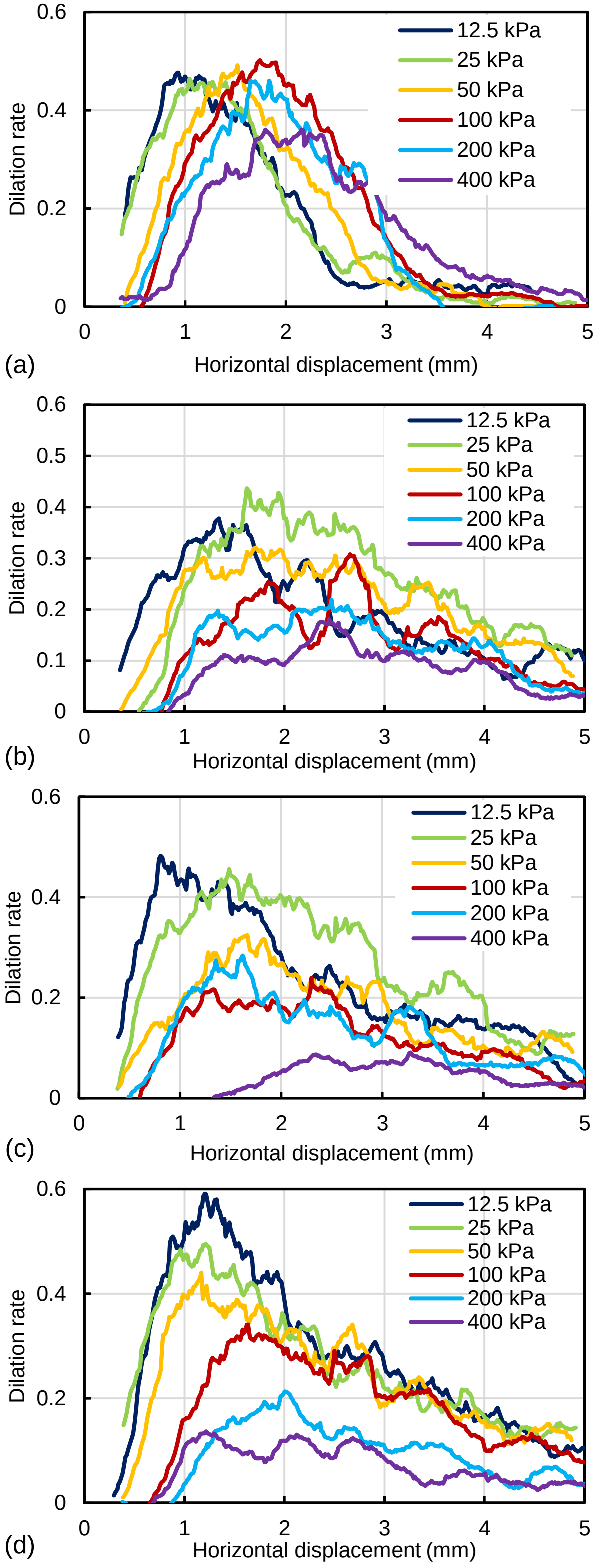

Figure 5. Dilation rate for compacted sand sample for varying moisture contents a) 0% (Dry), b) 1.5%, c) 3%, and d) 6%.

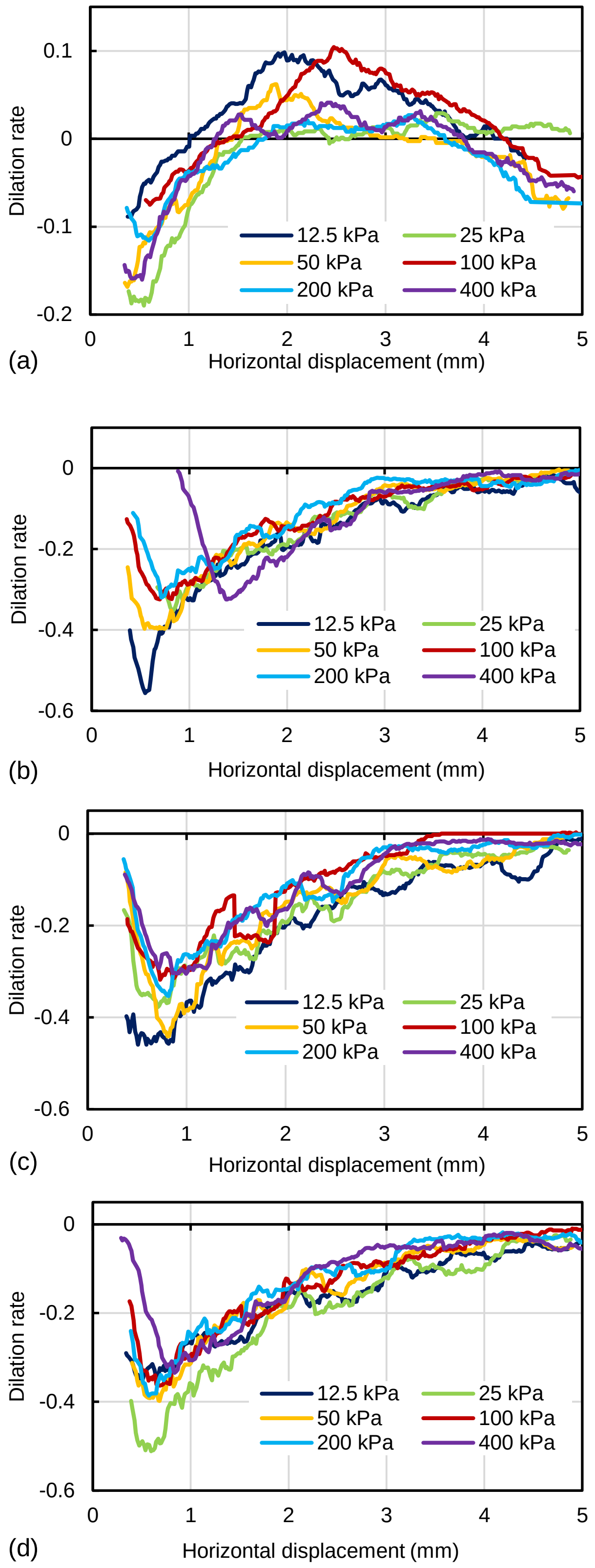

Figure 6. Dilation rate for uncompacted sand sample for varying moisture contents a) 0% (Dry), b) 1.5%, c) 3%, and d) 6%.

Figure 4 shows the stress–displacement behavior of the uncompacted (loose) sand samples. The moist sand samples reach the peak stress ratio at a higher horizontal displacement (~5 mm) for the loose condition than for the dry sand samples. The peak stress ratio for loose dry sand is around 0.7–0.9, which is close to the critical state value (0.6–0.8) of compacted dry sand discussed earlier. The peak stress ratio is the highest at 12.5 kPa of normal stress that decreases with the increase in normal stress.

Figure 5 plots the calculated dilation rate against the horizontal displacement for the compacted samples. Moving average values of the dilation rate are plotted in the figure to minimize the noise in the measured values. The post-peak degradation in dilation rate is found to be more significant for the dry sample (Figure 5). A similar scenario is observed in the case of peak stress ratio (Figure 3). The peak dilation rate for the dry sample is around 0.47–0.5 for all normal stresses except 400 kPa where it is 0.36 (Figure 5(a)). There is a rapid drop in dilation rate after reaching the peak values. The compacted moist samples show different peak dilation rates at different normal stresses. There is a gradual reduction of the peak dilation rate from 0.6 to 0.14 with the increase of normal stress from 12.5 kPa to 400 kPa for the sample with 6% of moisture contents (Figure 5(d)).

Dilation rates for the uncompacted loose sand samples are shown in Figure 6. The dry loose sands show some positive dilation rate with a maximum value of 0.1 over a shearing range (Figure 6(a)) which denotes an increase in volume. However, the moist sample shows negative dilation rate corresponding to the contraction that reaches close to zero dilation rate at high shear strains.

4.2 Peak Stress Ratio

Figure 7 shows the variation of peak stress ratio with normal stress for the compacted samples. Again, the peak stress ratio decreases with the increase in normal stress. The peak stress ratio at the lowest normal stress of 12.5 kPa is ~1.25 for all samples except for the sample with 6% of moisture content. The difference in peak stress ratio between the dry sample and moist sample increases with the increase in normal stress as the rate of changing stress ratio with normal stress is more in moist sand. Peak stress ratio is less in the moist samples, indicating a lower shear strength.

The variation of the peak stress ratio with normal stress for loose sand is shown in Figure 8. The peak stress ratio is reduced gradually from 0.93 to 0.68 with the increase of normal stress from 12.5 kPa to 400 kPa for the dry samples. However, the peak stress ratio of the moist samples remains almost constant (~0.67) for normal stresses between 100 and 400 kPa, indicating less effect of normal stress on the peak stress ratio of loose samples. Taylor (1948) observed from the triaxial tests on Ottawa sand that the angle of internal friction for loose condition decreases from 30° to 27° with increase of confining pressure from 48 kPa to 766 kPa whereas, for dense condition, it decreases from 34.5° to about 29° due to the same increase in confining pressure.

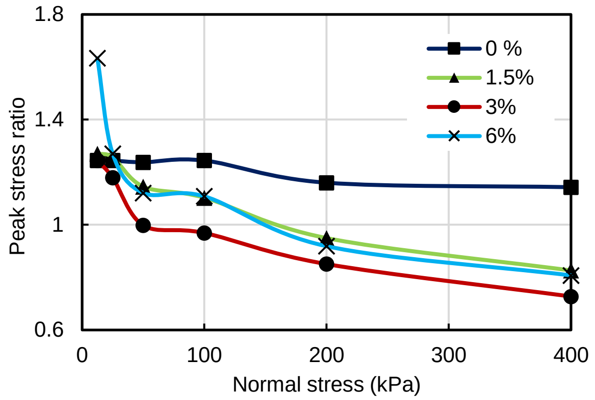

Figure 7. Effects of moisture content and normal stress on peak stress ratio for compacted sand samples.

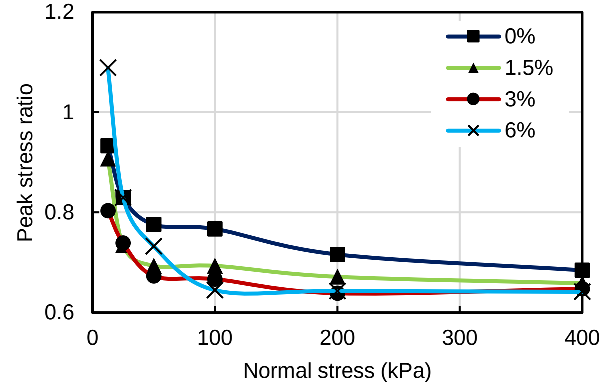

Figure 8. Effects of moisture content and normal stress on peak stress ratio for uncompacted sand samples.

4.3 The Angle of Internal Friction

The angle of internal friction and dry unit weight against moisture content plotted for the compacted samples are shown in Figure 9. The angle of internal friction is calculated from the slope of the linear trendline of the peak shear stress against six normal stresses considering zero cohesion. The maximum angle of internal friction of 49° is found for the dry sand, which is reduced to 37.5° with the increase of moisture content. Dry unit weight of the sand is also reduced with the increase of moisture content. The reduction of the angle of internal friction with moisture content is likely due to the reduction of dry unit weight. However, Tiwari and Al-Adhadh (2014) demonstrated for well-graded sand that the secant friction angle can decrease about 3.2° for changing from dry state to saturated state at the same relative density.

For the loose condition, the maximum angle of internal friction is ~34.5° for dry sand (Figure 10) that reduces with the increase in moisture content. The angle of internal friction for loose moist samples varies within a small range of 32.7°–33.5°, which is again consistent with the reduction of dry unit weight.

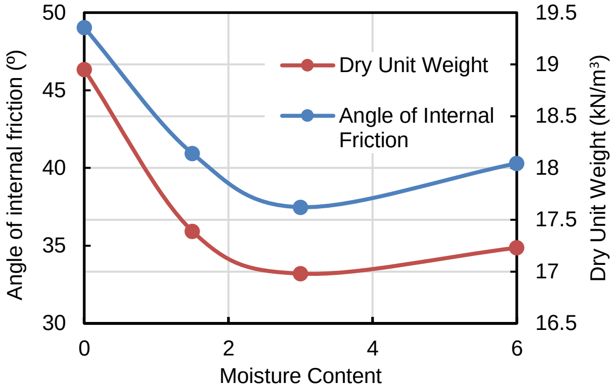

Figure 9. Effects of moisture content on angle of internal friction and dry unit weight for compacted sand samples.

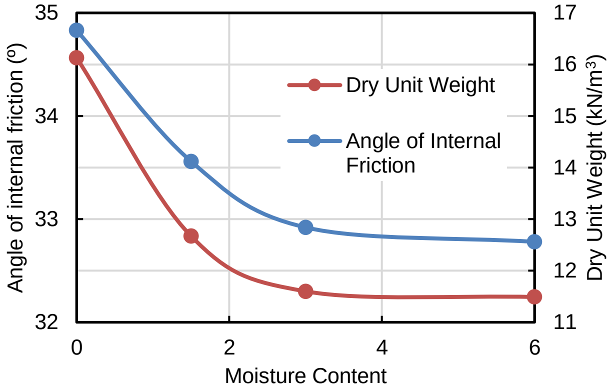

Figure 10. Effects of moisture content on angle of internal friction and dry unit weight for uncompacted sand samples.

4.4 Effect of Shearing Rate

The effect of the rate of shearing on the stress ratio is also studied under four normal stresses 50,100, 200, and 400 kPa for dry sand samples only. Figure 11 shows the variation of stress ratio with horizontal displacement changes in four shear displacement rates for the compacted samples. The peak stress ratio is obtained at 1.5 mm of horizontal displacement for each of displacement rate with 50 kPa of normal stress whereas for 400 kPa of normal stress it is obtained at 2.5 mm of horizontal displacement. There is no significant difference in peak stress ratio and post–peak degradation for different displacement rate in Figure 11.

Similar behavior is observed for the uncompacted samples as seen in Figure 12. Lade and Nam (2009) also reported no effect of shearing on the shear strength of the dry sand.

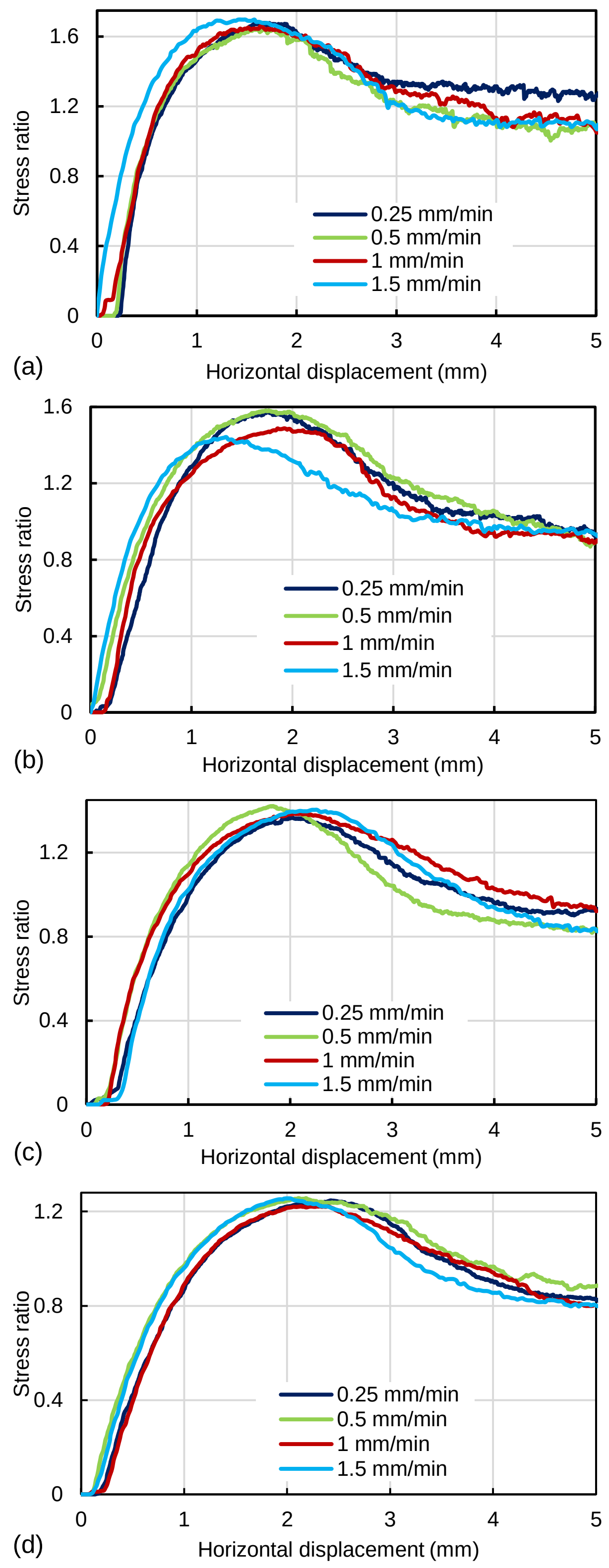

Figure 11. Stress ratio for compacted sand sample for varying shear displacement rates (mm/min) at normal stresses a) 50 kPa, b) 100 kPa, c) 200 kPa, and d) 400 kPa

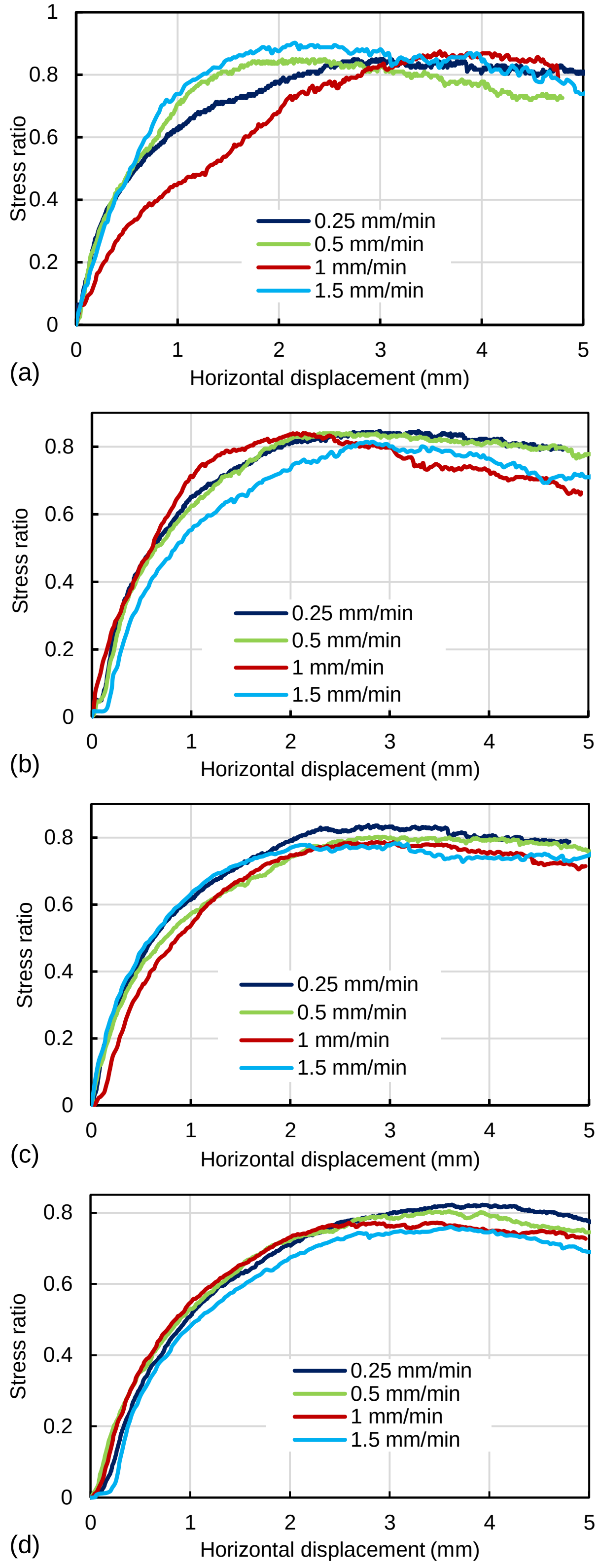

Figure 12. Stress ratio for uncompacted sand sample for varying shear displacement rates (mm/min) at normal stresses a) 50 kPa, b) 100 kPa, c) 200 kPa, and d) 400 kPa

5 CONCLUSIONS

This paper presents an investigation of shear strength and deformation behavior of a well-graded clean sand considering the effect of density, moisture content, relative compaction, and shear displacement rate using direct shear tests. The study reveals that the dry compacted sand sample has the post–peak degradation of stress ratio whereas the moist sand samples show less significant post–peak degradation. The peak stress ratio is found to decrease with the increase of normal stress for both dry and moist sands. The moist compacted sand samples show a higher reduction of peak dilation rate with increasing normal stress than that of the dry sand samples. The moist uncompacted sand samples show negative dilation whereas the dry sand samples show positive dilation within certain shearing range, indicating expansion of volume. The maximum angle of internal friction is found in the dry compacted sand samples which are reduced with the increase of moisture content. The variation of the angle of internal friction with moisture content is attributed to the change of dry unit weight with moisture content.

The dry sand samples show no significant change of stress–displacement behavior with the change of shear displacement rate.

6 ACKNOWLEDGEMENTS

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