Failure mode transitions of unconfined granular media from dry to unsaturated to “quasi-fully” saturated states

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Abstract. Recent research has shown discrepancies between the prevailing mathematical representations of near-surface shear strength and the observed shear strengths. This investigation focuses on three granular materials, i.e., 1) poorly-graded, medium-fine silica-quartz sand, 2) an engineered silica-quartz mix of 3.38-mm and 0.638-mm sub-angular particles, and 3) an angular fused quartz sand. Specimens were tested under load-controlled conditions at variable saturations in order to identify and quantify the influence of suction on the granular structures and failure modes. All three materials exhibited localized radial particle force chain buckling failures in unconfined drained dry (UD κ) conditions and classical shear failures in the unconfined drained unsaturated shear (UDP) conditions. In unconfined drained suction failures (UDS) conditions, the poorly-graded, medium-fine silica-quartz sand exhibited a bulging and sloughing failure without weeping, while the other two materials wept and then held loads before failure. Thus, it is suggested that the pore fluid had a predominate lubrication (strength weakening) effect, and the assumption of structure stiffening (strength increase) from matric suction may not be valid at near-surface conditions for sub-angular silica-quartz materials but is valid for the angular fused quartz.

1 Introduction

Understanding the true behavior of cohesionless soils immediately impacts the fields of internal erosion prediction, surficial sloughing in dams and levees, wave propagation, geo-sensor coupling, and geoenvironmental contamination and remediation designs. Laboratory experimentation on cohesionless soil fabric behavior in zero-to-low vertical confining pressure environments relies on the use of effective stress principles to infer behavior [1-3]. However, research suggests that the use of effective stress principles is not indicative of near-surface environments due to the application of confining pressures to maintain sample stability of granular materials. Moreover, recent research has shown discrepancies between the prevailing mathematical representations of near-surface shear strength and the observed shear strengths, e.g., Equation 1. This classical approach has proved sufficient for soils that are not at, or in close proximity to, the elastic free boundary of the soil-atmosphere interface.

$$\tau = c' + \sigma'_n \tan(\phi') + sS_r^\xi \tan(\phi') \quad (1)$$

where σ'_n is the normal effective stress along the failure plane, c' is the soil cohesion, ϕ' is the internal friction angle, and the sS_r^ξ parameter is used to account for the non-linearity suction strength from the soil-water characteristic curve (SWCC) that provides for additional

soil matrix strength in unsaturated soil mechanics [4]. More importantly, the mathematical representations require the assumption that the onset of failure is continuous along a single rupture plane at an angle, α , from horizontal to experimentally define ϕ' , as in Equation 2 [5].

$$\alpha = 45^\circ + \frac{\phi'}{2} \quad (2)$$

Taylor et al. [6] showed that the failure modes of unconstrained (free-standing) physical granular specimens do not conform to the assumption of simultaneous failure, especially under dry conditions. The purpose of this paper is to investigate the failure transitional modes observed in Taylor et al. [6] with respect to changes in particle size and shape, i.e., subangular and platy materials at different degrees of saturation.

2 Materials

This investigation focuses on three different granular materials, i.e., 1) poorly-graded, medium-fine silica-quartz beach sand (abbreviated here as S101), 2) an engineered silica-quartz mix of 3.38-mm and 0.638-mm sub-angular particles (E57-60), and 3) an angular fused quartz sand that is a refined slag byproduct with a platy

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crystalline structure (T101). Previous research on these materials can be found in several places in the literature [6-12]. None of the materials contained any fines or gravels. Engineering properties of the three materials can be found in Table 1, and the grain size distributions are provided in Figure 1.

Table 1. Material Properties.

Material	Specific Gravity	Dry Density (g/cm^3)	Water Content (%)	Saturation (%)
Poorly Graded Sand (S101)	2.67	1.69	5.32	24
Engineered Mix (E57-60)	2.62	1.82	6.09	36
Fused Quartz (T101)	2.24 [6]	1.43	5.30	21

4.1 Poorly Graded Sand S101

The S101 poorly graded sand failure can be seen in Figure 2. The specimen did not exhibit any bulging or other deformation before failure. The failure can be seen to propagate from the top down with approximately one third of the specimen failing at a time. Nine specimens failed under an applied axial stress ranging between 2.7 and 7.3 kPa, with an average of 5.2 kPa.

Fig. 2. S101 Dry UD κ Failure.

In the wet UD ρ specimens in Figure 3, a classical critical state shear plane is visible along with some bulging before failure. These specimens are weaker than the dry UD κ specimens with nine specimens failed under a vertical applied stress ranging between 3.7 and 4.6 kPa an average stress of 4.1 kPa.

Fig. 3. S101 Wet UD ρ Failure

For the wetting UD ς test, the nine specimens were wetted until they failed through slumping, as shown in Figure 4. No weights were applied. After failure, three moisture content samples were taken from the failed sample to determine the final moisture content. Specimens failed at an average saturation of 68.8%.

Fig. 4. S101 Wetting UD ς Failure.

4.2 Engineered Mix E57-60

The courser engineered mix E57-60 behaved largely the same as the clean sand S101, as can be seen for the UD κ specimens in Figure 5. Five UD κ specimens failed under a vertical applied stress ranging between 2.7 and 3.4 kPa with an average of 2.9 kPa.

Fig. 5. E57-60 Dry UD κ Failure.

E57-60 specimens again behaved similarly to the S101 specimens in UD ρ conditions, although the shear plane is not as pronounced in Figure 6 due to the coarser nature of the material. Eleven specimens failed under a vertical applied stress ranging between 2.7 and 4.6 kPa with an average of 3.3 kPa.

Fig. 6. E57-60 Wet UD ρ Failure.

The wetting specimens did not fail before the onset of weeping. Light weights were applied as can be seen in Figure 7. The entire specimen was dried to determine the moisture content. Five specimens failed at a saturation of 49% and under a vertical applied stress ranging between 0.1 and 0.7 kPa, with an average of 0.4 kPa.

Fig. 7. E57-60 Wetting UD_s Failure.

4.3 Fused Quartz T101

The fused quartz T101 material fabric structure is very fragile when dry. Five UD_k specimens initially stood for a minimum of 12 hours but collapsed under their own weight before the standard 48-hour drying period had elapsed. Upon inspection, the specimens were determined to not have reached a fully dry condition. The sixth sample is shown in Figure 9, with a similar failure pattern to the S101 and E57-60 dry specimens. This specimen failed under a 0.2 kPa applied axial stress.

Fig. 8. T101 Dry UD_k Failure.

The development of a shear plane can be observed in the failure of the T101 UD_p specimens in Figure 10. However, as the failure progresses, the weights fall straight down instead of following the angle of shear plane, and the material exhibits more of a radial failure. In contrast to the weak and fragile UD_k specimens, the three UD_p specimens failed under a vertical applied stress ranging between 13.9 and 16.3 kPa with an average of 15.2 kPa, i.e., strengths much higher than those observed for either of the silica-quartz sands.

Fig. 9. T101 Wet UD_p Failure.

The T101 UD_s specimens did not fail in a consistent manner after the onset of weeping. Of the four specimens, two exhibited a shear failure similar to the classical shear failure of the wet clean sand, as shown in Figure 10. The other specimens were more similar to the UD_p T101 samples, with more development of a shear plane combined with radial granular ejecta. The entire specimen was dried to determine the moisture content. Four specimens failed at a saturation of 55% and under a vertical applied stress ranging between 8.4 and 12.1 kPa, with an average of 10.4 kPa.

Fig. 10. T101 Wetting UD_s Failure.

5 Discussion

5.1 Unconfined drained dry (UD_k)

All three materials exhibited localized radial particle force chain buckling failures in unconfined drained dry (UD_k) conditions suggesting that failure stress is not uniform throughout the specimen. Pixel matching of high-resolution photographs showed no axial or radial deformation before failure. The failures propagate down from the top of the specimen with radial granular ejecta. In the both the subangular S101 and E57-60 sands, the failure can be seen to begin in the top third of the specimen, while in the platey-shaped T101 material, the failure is in the upper two thirds. The T101 fabric structure is also much weaker and more fragile than the

others due to less contact friction between the particle plates.

In all cases, the combination of localized buckling failures and no observable deformations prior to the onset of failure suggest that conditions for simultaneous failure is violated. This is further evidenced as Equation 1 suggests that an unconfined dry granular material will not exhibit a shear resistance, which is in contrast with physical experimentation and observations.

5.2 Unconfined drained unsaturated shear (UD_p)

All three materials exhibited classical shear failures in the unconfined drained unsaturated shear (UD_p) conditions. Due to the grain sizes, the critical failure plane is most visible in the S101 material. In the case of these types of failures there is a distinct transition to a simultaneous failure condition due to the inclusion of soil suction in the partially saturated regime. However, this presents an unresolved query of how soil suction should be accounted for in terms of the failure shear stress. Namely, if suction has the effect of generating an effective confining pressure and increasing α , then should the effects, in an unconfined state, be counted twice, i.e., once in the increase of the effective friction angle and a second time in the addition of a suction parameter?

5.3 Unconfined drained suction failure (UD_s)

In unconfined drained suction failure (UD_s) conditions, the poorly-graded, medium-fine silica-quartz sand exhibited a bulging and sloughing failure without weeping at approximately 70% saturation. However, the other two materials exhibited an onset of weeping before failure due to larger pore space providing rapid drainage of the added water. The E57-60 material quickly fell under a load less than 1 kPa. Due to significant suction effects of the platy grain structure, the T101 samples held an average of about 10 kPa.

In the case of the S101 material, the specimens exhibited a non-uniformity in slumping. This suggests, as with the dry cases, that failure does not necessarily meet the simultaneous rupture criteria. Thus, in the case of Equation 1, the predicted strength would be in excess of the observed lack of shear resistance. Conversely, the E57-60 and T101 samples, due to their inability to continuously retain additional pore fluid, do exhibit a strength increase due to suction and a more simultaneous failure mode. However, the same unresolved query of accounting for the effects of suction twice still remains for these samples.

6 Conclusions

For sub-angular silica-quartz sand, it is suggested that the pore fluid had a lubrication (strength weakening) effect, and the assumption of structure stiffening (strength increase) from matric suction may not be valid at near-surface conditions. However, the effects of suction are very pronounced on the platy crystalline

structure of the fused quartz sand and contribute to a large increase in strength between the dry and wet conditions and only a mild strength loss at the point of weeping.

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