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Cohesionless soil fabric behavior at low confining pressures

Comportement du structure de sol sans cohésion à des pressions de confinement faibles

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ABSTRACT: Mohr-Coulomb strength is significantly influenced by vertical effective confining pressures but does not adequately describe soil behavior under low confining pressures. The objective of this study was to evaluate soil behavior for a poorly-graded clean sand (SP) in this environment. Methods included: simple shear and triaxial specimens with confining pressures ranging from 0 to 100 kPa; static and dynamic flow conditions using the Ultrasonic Near-Surface Inundation Testing (UNIT) device to test near-surface saturation effects on the internal soil structure through shear wave propagation; and unconfined, self-supported cylindrical specimens to evaluate the failure mechanisms and internal fabric structure. The results show significant deviations from expected current soil mechanics theory. Triaxial and simple shear specimens exhibit an additional strength of 5-10 kPa at low confining pressures. Similarly, freestanding specimens withstood 2.6-7.7 kPa. The inclusion of moisture significantly impacts the quantification of v_s and the internal structure's ability to propagate shear energy. Results across testing methods show soil strength in low confinement environments is not negligible and can have a significant impact in a variety of applications.

RÉSUMÉ: La force de Mohr-Coulomb est fortement influencée par des pressions de confinement effectives verticales mais ne décrit pas correctement le comportement du sol sous des pressions de confinement faibles. L'objectif de cette étude était d'évaluer le comportement du sol pour un sable propre mal classé dans cet environnement. Les méthodes utilisées ont consisté à: cisaillement simple et échantillons triaxiaux avec des pressions de confinement allant de 0 à 100 kPa; Statiques et dynamiques à l'aide du dispositif d'essai d'inondation de surface à ultrasons (en anglais le nom est Ultrasonic Near-Surface Inundation Testing, UNIT) conçu pour tester expérimentalement les effets de saturation près de la surface sur la structure interne du sol par la propagation des onde de cisaillement; Et des éprouvettes cylindriques auto-supportées non confinées pour évaluer les mécanismes de défaillance et la structure interne. Les résultats montrent des écarts significatifs par rapport à la théorie actuelle des mécaniciens du sol. Les échantillons de cisaillement triaxial et simple présentent une résistance supplémentaire de 5 à 10 kPa à des pressions de confinement faibles. De même, les spécimens autoportants ont résisté à 2,6-7,7 kPa. L'inclusion d'eau, à la fois dans les conditions d'écoulement statique et dynamique, a un impact significatif sur la quantification de v_s et la capacité de la structure interne à propager l'énergie de cisaillement. Nous concluons que l'estimation actuelle du comportement du sol dans des environnements à faible confinement n'est pas négligeable et peut avoir un impact significatif dans une variété d'applications.

KEYWORDS: Soil Fabric; Soil Behavior; Low Confining Stress; Laboratory Testing, Partially Saturated Soil

1 INTRODUCTION

Understanding the true behavior of cohesionless soils immediately impacts the fields of internal erosion prediction, surficial sloughing of dams and levees, wave propagation, geo-sensor coupling, and geoenvironmental contamination and remediation designs. Laboratory experimentation on cohesionless soil fabric behavior in low-to-zero vertical confining pressure environments relies on the use of effective stress principles to infer behavior (Fannin et al. 2005; Huang et al. 2015; Lancelot et al. 2006). However, effective-stress-based laboratory tests are not indicative of low-confining pressure in situ environments.

In all cases of soil mechanics, a soil element's ability to resist shear rely on a summation of individual components of strength, 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.

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

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 (Han & Vanapalli 2016). For most geotechnical problems, Mohr-Coulomb mechanics yields relatively accurate approximations due to moderate to high confining stresses. However, the failure plane suggested by Mohr-Coulomb mechanics may not be the actual failure plane upon which shear strains concentrate under near-surface environments.

The objective of this study was to evaluate soil behavior for a poorly-graded clean sand (SP) in the near-surface environment in order to document deviations from expected theory. Testing included simple shear and triaxial specimens with confining pressures ranging from 0 to 100 kPa; static and dynamic flow conditions using the Ultrasonic Near-Surface Inundation Testing (UNIT) device designed to experimentally test near-surface saturation effects on the internal soil structure through shear wave (v_s) propagation; and unconfined, self-supported cylindrical specimens to evaluate the failure mechanisms and internal fabric structure.

1 .1 *Materials*

The sand used for this study is a washed, uniform, medium-to-fine beach sand (SP). The material is poorly graded with 90 percent of the material between 0.25 and 0.85 mm in diameter. The Coefficient of Uniformity is 1.52, reflecting the dominance of the No. 40 and No. 60 sieves in the grain-size distributions. The Coefficient of Curvature is 1.12. The specific gravity is 2.70. Specimens were compacted to a density of 1.65 g/cc (Index Density of 0.21) and water content of 5.66 percent, reflecting 24 percent saturation and loose-to-medium dense specimens in accordance with Taylor et al. (2016a).

2 TEST RESULTS

2 .1 *UNIT testing*

Taylor et al. (2014) observed that near surface post-rain signals are amplified up to 14.7 fold over the pre-rain signals with significant shifts in spectral content at low to negligible confining stresses. Shifts in spectral content of a shear wave crossing a fracture or multiple fractures that are on the order of the wavelength have been studied, yet these studies do not replicate the behavior observed in field deployments (Pyrak-Nolte et al. 1990; Pyrak-Nolte and Nolte 1992). To experimentally replicate and understand these effects in a controlled environment a new testing apparatus needed to be designed specifically for the low confining stress, near-surface environment: the Ultrasonic Near-surface Inundation Testing device developed at the US Army Engineer Research and Development Center (Martin et al. 2014; USPTO #14/920,385).

The data for the wetting-drying cycles can be seen in Figures 1-4. Literature indicates that, in saturation experiments with full confinement, three cycles are determined to be sufficient for stable soil fabric and repeatable results. However, these data indicate that under near-surface conditions stability of the soil fabric is not achieved. The frequency content indicates two peaks, a dominant lower value peak and a secondary higher value peak, emerge with successive wetting/drying cycles, see Figure 4. The relative energy in each peak is dependent on location on the saturation cycle curve. In the FFT space, the increase in amplitude correlates to a better coupling with water in higher saturation contents. The changes in wave characteristics, as shown a Figures 1 through 4, suggest a change in fabric structure after each cycle, thus the assumption of constant porosity, and associated density, is not valid. The governing assumption is that the bender element is measuring the shear field both as input and output, but the data show that the input shear field is not ‘pure’, that is the cycle input and output results do not correlate. Figures 1-4 show the effect of saturation variability on media response to the propagation of shear waves as measured in millivolts (Mv), suggesting that under near-surface conditions the soil fabric undergoes a previously undefined failure state during the wetting/drying cycle not explained in traditional mechanics.

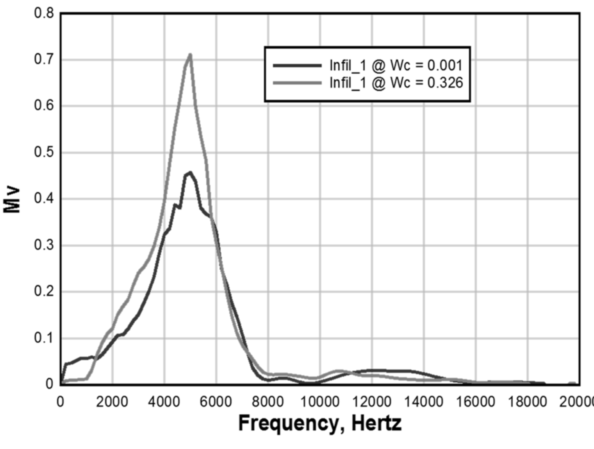

Figure 1. Frequency Response For First Wetting Cycle Subjected To a 10 kHz, 1-s, 14 Volt Sine Wave Driver

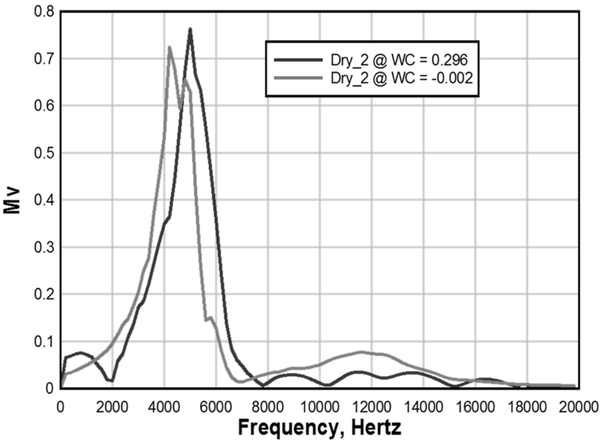

Figure 2. Frequency Response For First Drying Cycle Subjected To a 10 kHz, 1-s, 14 Volt Sine Wave Driver\

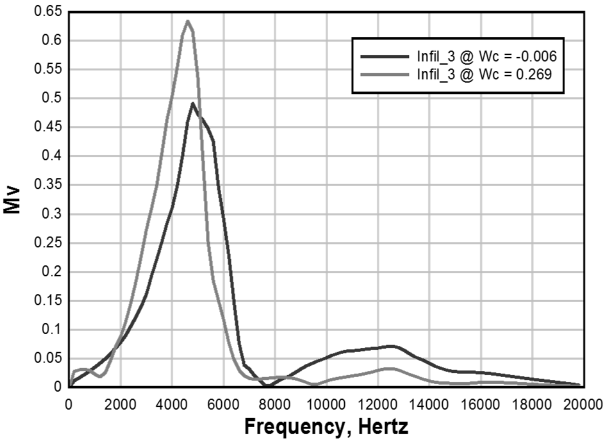

Figure 3. Frequency Response For Third Wetting Cycle Subjected To a 10 kHz, 1-s, 14 Volt Sine Wave Driver

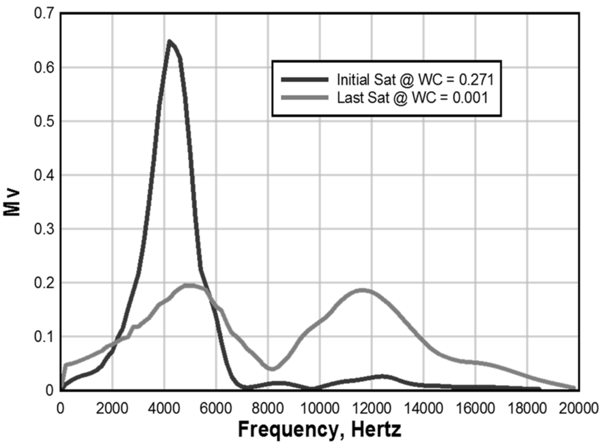

Figure 4. Frequency Response For Third Drying Cycle Subjected To a 10 kHz, 1-s, 14 Volt Sine Wave Driver

2 .2 *Triaxial and simple shear testing*

Triaxial specimens measured 71.9 mm in diameter by 145.0 mm in height. Specimens were tested at confining pressures of 0, 15, 25, 50, 100, 500, and 1000 kPa, with three repetitions at each confining pressure for a total of 21 tests. Triaxial failure strength was determined at the point of maximum deviator stress.

The expected Mohr-Coulomb failure plane was defined using test results of ICD_{TX} tests conducted with confining pressures of 100, 500, and 1000 kPa. A trendline was fit to the test results in p-q space assuming a cohesion intercept of zero, consistent with assumptions for a cohesionless materials (Lambe and Whitman 1969).

Results of all of the triaxial tests plot above the theoretical failure envelope; the test results under 50 kPa can better be represented by a steeper friction angle (38.9°) and a 6.05 kPa intercept.

Simple shear specimens measured 72.9 mm in diameter by 32.0 mm in height. Specimens were tested at confining pressures of 0 (six tests), 15, 25, 50, 75, 100, 250, and 500 kPa, and 5 kPa vertical seating loads, with three repetitions at each confining pressure for a total of 27 tests. Simple shear failure strength was determined as the maximum shear stress at or below 3.5 percent shear strain for specimens tested at or below 100-kPa cell pressure, 7.5 percent shear strain for specimens tested at 250-kPa cell pressure, and 10.0 percent shear strain for specimens tested at 500-kPa cell pressure to correspond to observed plateauing of the shear stress relative to the shear strain.

Similar to the observations with the triaxial results, the failure envelope deviated from the theoretical failure plane at low confining pressures. Under near-surface confining pressures, the observational failure plane can be best described by a second-order polynomial (R^2 =0.988) with a 5.54 kPa intercept that rejoins the theoretical failure envelope near 100 kPa.

The greatest difference between the expected Mohr-Coulomb failure plane and the observational envelope occurred at about 50 kPa. The effects of the soil continuum fabric decrease with increasing confining pressure until the observational envelope rejoins the Mohr-Coulomb failure line at 100 kPa.

Results from both triaxial and simple shear tests for confining pressures up to 100 kPa are shown in Figure 5.

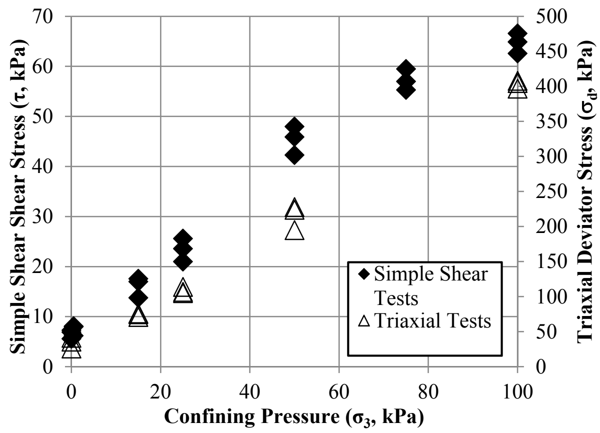

Figure 5. Triaxial and Simple Shear Testing Results

2 .3 *Failure mechanism testing*

Under near-surface conditions, Equation 1 can be deconstructed into three distinct failure mechanisms; (1) soil fabric strength evidenced by a bulk failure; (2) matrix suction strength evidenced through sloughing failure; and (3) internal planar friction defined by the classical formation of an internal shear plane, Equations 2-4. Through unconfined-drained (UD) self-supporting cohesionless sand samples, each failure mechanism is isolated, quantified, and captured via high-resolution (1280x800 dpi), high-speed videography (389 pps).

$$\tau_p = \sigma'_n \tan(\phi') \quad (2)$$

$$\tau_s = sS_r^{\xi} \tan(\phi') \quad (3)$$

$$\tau_\kappa = \kappa \quad (4)$$

In an unconfined state, each of these components should then be isolated and quantified. In Equation 2, τ_p, is the planar friction within the soil. In a classical sense, this is frictional resistance of a block sliding down an inclined plane (Peck et al. 1953). The internal friction angle, *φ'*, is dependent on the granular properties of the soil, e.g., particle shape, mineralogy, etc., and the normal force applied along the shear plane. In the case of κ, the quantification of fabric strength would be one half of the maximum applied shear (deviator) stress on a dry specimen, Equation 4. The measurable moisture content must be negligible to isolate this constitutive component. Without the presence of pore fluid, the saturation ratio becomes zero, and the influence of suction, as defined in Equation 3, disappears. Further, without suction there is no capillary confinement (gage) stress, and theoretically the internal shearing plane would have a *φ'* of zero eliminating the planar shear constitutive component, Equation 2. In Equation 3, τ_s is soil's strength garnished by suction forces to include the contractile skin of the internal pore fluid and is also a function of the internal friction angle due to the influence of granular properties.

If the constitutive components of Equation 1 are independent, then a loading scenario in which the applied deviator stress exceeds more that one failure surface must be possible. The resulting failure mechanics must exhibit properties of the exceeded failure surfaces, thereby illustrating the independence of the constitutive components and behavioural characteristics within the near surface. To validate the theory, a high stress unconfined test, (HS 2-Yield Surface Failure in Figure 6), was performed wherein the final load increment applied was large enough to exceed to yield surfaces, τ_p and τ_κ, in a single increment. The failure mechanics for each failure type are shown in Figure 6.

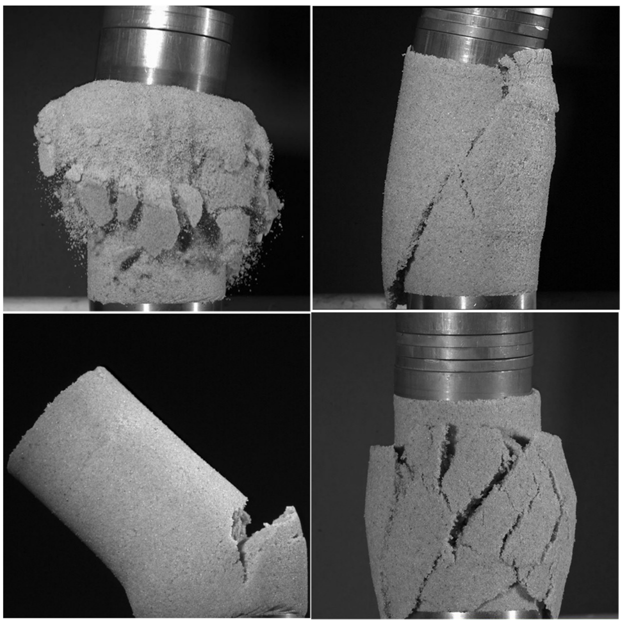

Figure 6. Constitutive Failure Planes Within The Near-Surface. Clockwise from top left: fabric failure (Eq. 4), planar failure (Eq. 2), multi-plane failure [HS 2-Yield Surface] (Eq. 2 &4), and suction failure (Eq. 3).

3 DISCUSSION

The failure mechanics testing is designed to resolve how cohesionless soil behaves near the origin (or x-axis zero intercept) of Figure 5. Traditionally, the failure surface is assumed and mathematically annotated to go through the origin and then the failure plane is "fit" to the experimental Mohr's circles. The actual behavior, Figure 5, is not represented by this assumption. While the deviation between the assumed origin-based failure line and the actual behavior may seem minor in magnitude, Figure 7, the characteristic behavior and applied stress method, e.g., shear, axial fluid infiltration, etc., define the ultimate strength until the confining pressures dominate the ability of the soil particles to govern the holistic behavior and the soil element behaves as a confined continuum, i.e. continuum mechanics.

In traditional mechanics, φ' is an independent characteristic property of the soil at a given index density, I_d; ranging from 0.0 (the loosest condition by which no volumetric strain is observed during typical backpressure saturation in a standard triaxial test, ρ_d=1.618 g/cc) to 1.0 (density correlating to Modified Proctor density, ρ_d=1.717 g/cc). However, in near-surface conditions φ' varies from the characteristic Mohr-Coulomb failure line typically used to derive φ'. The change in the φ' for this region of low confinement can be attributed to the inclusion of confining stresses (e.g., K_0 confinement with depth). Once a confining stress, an exterior force, is applied, the soil will no longer behave under near-surface conditions, and the independent constitutive components (and respective failure surfaces) become additive components of the holistic shear strength, Equation 1. With low confinement stresses, the τ_p failure plane exceeds that of τ_s and τ_κ, thereby becoming the dominant factor in strength determinations. Provided that τ_p is within relative proximity to the magnitudes of τ_s and τ_κ, there should be an observed increase in shear strength in relation to the traditional Mohr-Coulomb failure line. This is the case that is observed in Figure 5. Moreover, with an external confining pressure, the failures of τ_s and τ_κ are restricted in their respective ability to cause deformation. The near-surface failure planes are shown in Figure 7.

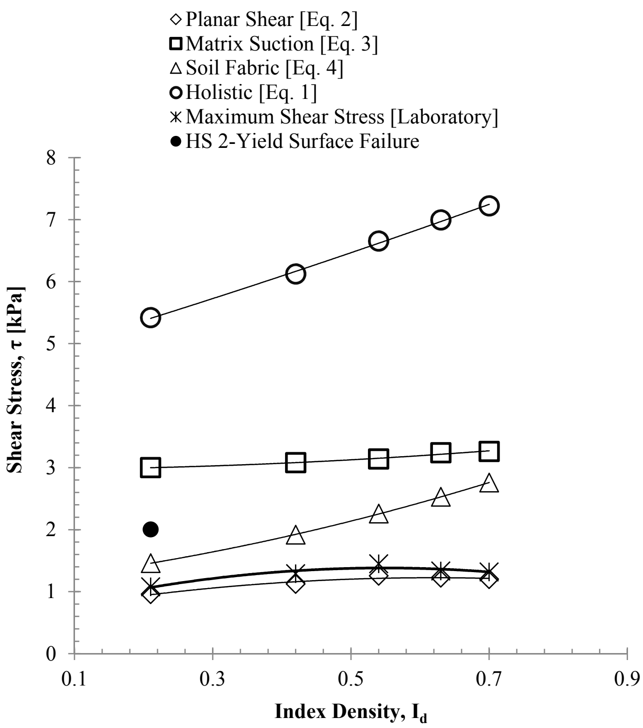

Figure 7. Failure Surfaces Under Near-Surface Confinement. Additional index densities shown to illustrate trends.

4 SUMMARY

For most geotechnical problems, traditional Mohr-Coulomb mechanics yields relatively accurate strength approximations. However, the actual shear strength may not be adequately represented by Mohr-Coulomb mechanics under near-surface environments, and such a deviation in constitutive governance can have significant impacts on near-surface soil behaviour and geotechnical and geophysical sensor performance (Taylor et al. 2014; Martin et al. 2014; Taylor et al., 2016b; Winters et al. 2016). Additionally, understanding the true nature of near-surface soil mechanics would have immediate impacts in erosion/scour predictions, surficial sloughing of dams and levees, and geoenvironmental contamination/remediation designs.

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