Effects of Wetting on the Shear Strength of Plastic Silty Sands

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ABSTRACT: This paper presents the results of intensive laboratory testing program investigating the effects of wetting on the drained shear strength and deformation characteristics of silty sands. The materials used were clean medium to fine grained Nile River bed sand and plastic Nile silt. The sand was mixed with 4%, 8%, 12%, 16%, 25% and 40% by dry weight of the Nile silt. The test specimens were prepared at two relative densities 30% and 79.4% and drained direct shear tests were performed on air dry and wetted “submerged” specimens. Results from the tests, i.e. shear stress versus displacement and volume change versus displacement, were analyzed and discussed. The dry specimens showed compression and then dilation during shearing. The volume change behavior of wetted silty sands depends on the silt content and the relative density. With silt content up to 25%, the wetted loose silty sands compressed during shear whereas the wetted dense mixtures showed compression and then dilation during shear. The wetted specimens with fines content of 40% showed compression only during shear. The wetted specimen with (sand + 40% fines) behaved like fine grained soil. Significant drop in shear strength caused by wetting has been measured for all tested specimens. The drop in shear strength was greater for the dense specimens compared to the corresponding loose ones. The drop showed general trend of increase with fines content.

INTRODUCTION

The properties of clean sands pertaining to shear strength have been studied extensively under laboratory and field tests. In nature natural sands are often mixed with plastic or non-plastic fines. The mechanical response of sands which contain significant amounts of silt and/or clay is different from that of clean sands. When granular soils contain a certain amount of fines, the strength characteristics vary with fines content. However they are evaluated as pure sands and correlations of in-situ tests are based on charts and relationships that have been developed for clean sands. Further understanding of the factors contributing to the shear strengths observed for
silty sands, both in laboratory and in the field and the role of fines on the reduction or increase in shear strength, would help in the formulation of a consistent method for strength characterization of sandy soils containing fines.

Khartoum city is covered with thick alluvial formations mainly deposited by the Blue Nile (Mohamed 2001). These formations constitute an upper blanket of very stiff to hard silty clay of high plasticity underlain with loose or medium dense clayey silty sand, and then dense poorly graded sand. The alluvial formations overlie old formations known as Nubian Sandstone formation (Mohamed 2001). Water table depth varies depending on the distance from the Blue Nile. The clayey silty sand or sandy silt are often subject to periodical wetting and drying caused by the fluctuating water table. The shear strength of the clayey silty sand given the variation in fine content and wetting conditions needs evaluation and research.

The objective of this laboratory study is to investigate the effects of fine content (plastic silt clay mixture) and wetting on the shear strength of plastic silty sands.

THE FACTORS AFFECTING SHEAR STRENGTH OF SILTY SAND

Research has been carried out during the last few decades to study the behavior of silty sands. These works indicated that the mechanical response of silty sands is different from those of clean sands and that the amount of non-plastic fines and the void ratio of the samples affect silty sand behavior (Thevanayagam, 1998, Sitharam et al., 2004).

Many factors were found to affect shear strength of silty sands such as confining stress (in triaxial) or normal stress (in direct shear), void ratio, relative density, fines content and soil state (whether dry or wet). Thevanayagam (1998) and Sitharam et al. (2004) observed from experiments on silty sands that the residual strength decreases with increase in the void ratio. Furthermore, the residual strength increases with increasing effective confining pressure. Yamamuro and Lade (1998) mentioned that for loose silty sands, the friction angle indicates the lowest value at the lowest initial confining pressure. The friction angle then increases to its peak value at the highest confining pressure. According to Sitharam et al (2004), increase in relative density results in an increase in the residual strength at a given confining pressure. Thevanayagam et al. (2002) from their experimental studies on undrained strength of silty sand (12% to 32% fines) at a confining pressure of 100 kPa, reported similar behavior of increasing residual strength with increasing relative density.

Sitharam et al., (2004) found that silty sands in the void ratio range of 0.607 to 0.656 show drastic reduction in strength at lower confining stresses and exhibit more dilative behavior at higher confining stresses. Thevanayagam (1998) conducted series of undrained triaxial compression tests to investigate the effect of fines, intergranular void ratio, defined as the void ratio of the original coarser-grain matrix structure if the fines were removed from the structure, and initial confining stress, and to quantify their impact on undrained shear strength of silty sand. Results indicated that; the intergranular void ratio plays an important role on undrained shear strength Sus of silty sand. Salgado et al., (2000) performed a series of triaxial and bender element tests to find how the shear strength and small-strain stiffness of Ottawa sand change as an increasing percentage of nonplastic fines are added to it. The tests were conducted on
isotropically consolidated sand samples with 0, 5, 10, 15 and 20% nonplastic fines. The results were analyzed to assess both the peak and the critical-state friction angles of clean and silty Ottawa sands. It was observed that the addition of even small percentage of silt to clean sand considerably increases both the peak friction angle at a given initial relative density and the critical-state friction angle. They noted that although small-strain stiffness drops, peak and critical-state strengths increase with increasing fines content.

MATERIALS

The materials used in this study were, coarse sand with sub-rounded quartz particles brought from Nile river bed in the vicinity of Merowi Dam in Northern Sudan, known as Marwa sand and Nile silt from the flood plain of the Blue Nile at Soba area South of Khartoum, Sudan. The physical properties of the sand and the silt are summarized in Table 1. Specific gravity and relative density tests were performed to find the minimum density by ASTM D 4254 and maximum density by ASTM D 4253 for Marwa sand. Based on the Unified Soil Classification System (USCS) the sand is classified as poorly graded sand SP, and the silt is classified as low plastic clayey silt ML.

Table 1. Properties of the Nile silt and Marwa sand

<table>
<thead>
<tr>
<th>Soil Parameter</th>
<th>Plastic Silt</th>
<th>Marwa Sand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific Gravity</td>
<td>2.79</td>
<td>2.81</td>
</tr>
<tr>
<td>Liquid Limit</td>
<td>43</td>
<td>non-plastic</td>
</tr>
<tr>
<td>Plastic Limit</td>
<td>31</td>
<td>non-plastic</td>
</tr>
<tr>
<td>Sand content</td>
<td>20%</td>
<td>100%</td>
</tr>
<tr>
<td>Silt Content</td>
<td>70%</td>
<td>0</td>
</tr>
<tr>
<td>Clay Content</td>
<td>10%</td>
<td>0</td>
</tr>
<tr>
<td>Minimum void ratio</td>
<td>-</td>
<td>0.9</td>
</tr>
<tr>
<td>Maximum void ratio</td>
<td>-</td>
<td>0.47</td>
</tr>
<tr>
<td>Classification (USCS)</td>
<td>ML</td>
<td>SP</td>
</tr>
</tbody>
</table>

TEST PROGRAM AND METHODS

The test program comprised performing direct shear tests on pure sand and sand mixed with different quantities of fines. The tests were carried out at two density states (loose and dense) and for dry and wetted conditions. Since Marwa sand and the Nile silt consist of different sand, silt and clay contents (Table 1), specific quantities of the two soils were air dried and then mixed to get soil with overall fines content equals (Marwa sand 0%, 4%, 8%, 12%, 16%, 25%, 40% and 60%) of the total dry weight. The sand with 60% silt content represents fined grained soil according to the Unified soil Classification system (USCS).

The samples were prepared by manual tamping in the shear box at two different dry densities. Sufficient quantities of the mixes were weighed to guarantee that all the specimens being prepared for each percentage were identical. The specimens were prepared at the two target densities (void ratios) of the silty sand specimen ($\rho_1 = 1.59$)
g/cm³ and ρ₂ = 1.80 g/cm³ (e₁ = 0.77 and e₂ = 0.56) equivalent to relative densities equal to 30% and 79.4%. It was not possible to prepare the dense sand+60% silt. The test was carried out on three similar (identical) specimens having the same fines content and dry density. The vertical normal pressures (50, 100 and 150 Kpa) were applied on the specimens.

As for the wetted tests, wetting was performed by adding distilled water to the specimen in the shear box. It was intended to create or simulate submerged conditions in the field. The specimens with low percentages of fines (0, 4, 8, 12 and 16%) were inundated for two to six hours, whereas the specimens with relatively high percentages of fines (25%, 40% and 60%) were inundated for one day. Compression of the sample was accomplished by applying the vertical stress on it for a time span ranging from 5 minutes for all dry samples to 120 minutes for wet samples with low fines content (0, 4, 8, 12 and 16%) and 24 hours for wet samples with relatively high fines content (25%, 40% and 60%). The samples were then sheared at a suitable horizontal rate of displacement for drained conditions; 0.1 mm/min for pure sand and low fines content (less than 12%) and 0.06 mm/min for high fines content (≥ 16%). These rates were determined from the results of one dimensional consolidation tests following the procedure described in Head (1994). The test data was plotted in two formats, shear stress versus horizontal displacement and vertical displacement versus horizontal displacement (Saad, 2010). The test results were then placed in three groups based on their similarity in response to shearing. The first group covers the stress-strain and stress-volume change relations for dry and wetted pure Marwa sand; the second presents the same relations for sand mixed with 4%, 8%, 16% and 25% silt content and this one could be represented by the sand+8% silt; the third presents the data for sand + 40% and 60% silt.

ANALYSIS AND DISCUSSION

The results from the tests will be analyzed and discussed to gain information on the influences of fines content and wetting "submergence" on the stress-strain relationships and volume change during shear, i.e., dilation and compression of the tested samples for loose and dense states.

Shear Stress versus Displacement Relationship

The shear stresses versus displacement curves for pure sand (Figure 1) are typical of those of other types of sands. The dense sand showed increase in stress with strain up to a peak shear resistance, after which the shear resistance dropped displaying work-softening to ultimate values. The drop was sharper for the higher vertical loads. The loose samples showed a small peak at very low strain followed by a drop in shear resistance, a sign of a slip, then increase in shear resistance to ultimate values for dry and wetted samples. The shape of the wetted dense samples was similar to that of the corresponding dry samples; however, the resistance to shearing was lower than those of the dry samples. The shear stress-strain response of the loose wet samples is similar to that of the loose dry samples except that the peaks are not displayed.
The shapes of the shear stress versus displacement curves for dry and wetted sand containing 8% silt samples, which are representative of 4% to 25% silt content, look similar to those of the pure sand, except that the magnitudes of the maximum shear stress and the corresponding displacement are different.

The stress displacement curves for dry sand + 40% silt and 60% (loose) look about similar to those of sand+8%, sand+12% sand+16% and sand+25% ones “for dry samples” with slightly flatter curves around the peak values of stress. However, for the wet sand+40% and 60% silt the stress increased with strain to ultimate value beyond which the resistance to shear was constant (Figure 2). The peak was experienced at a horizontal displacement of 1.0 to 1.5 mm. An important observation is that, the stress strain relationships for wetted dense and loose sand+ 40% silt are similar to those of saturated fine grained soils as represented by sand+60% silt. Therefore, the shape of the stress-displacement curves is affected by the fines content and wetting conditions, combined. As for the dry sand+silt samples, the shapes of the stress-displacement curves look about similar irrespective of the silt content, but the influence of the silt becomes more noticeable for the wetted specimens. When the silt content is 40%, the peak stress is not displayed for all the wetted samples (loose and dense) and the shapes of the stress-displacement curves become similar to those of sand+60% silt or those of fine-grained soils.
FIG. 2. Shear stress - horizontal displacement for wetted sand soil contains 40% fines at relative densities 30% & 79.4%

This study has clearly shown that shear strength decreases as the soil is wetted "submerged" for different values of fines content (4%, 8%, 12%, 16%, 25% and 40%) at different relative densities (30% and 79.4%) and different applied normal stresses. The peak shear strength was plotted against fines content for dense, loose, dry and wetted test conditions for a normal stress of 100 kPa (Figure 3). The loss of strength as depicted by the difference between the peak shear resistance for the dry and wetted conditions is more pronounced for fines content up to 16% for both loose and dense states. However, the drop is smaller for 25% fines and greater percentages of fines, especially for the loose samples. The loose samples were less affected by wetting compared with the dense ones and the drop in peak strength ranges between about 5 to 38%.

On evaluating the shear strength characteristics of the dry and submerged plastic silty sands, prepared at the same relative density and silt content, the main factors that could influence their strength and volume change characteristics are matric suction and mineralogy of the clay fraction. The value of matric suction of a dry tested specimen depends on its silt content, which controls its pore size distribution, porosity and dry density. However, the matric suction of the submerged wetted samples is almost zero since enough wetting time was allowed prior to performing the direct shear test. The drop in peak strength caused by wetting for a sample with the same dry density and silt content could be partly attributed to the dissipation of matric suction, resulting in lower effective stress and lower resistance to shearing. Another factor is the plasticity of the fines and their mineralogy. Mineralogical analysis of the Nile silt, which constitutes 10% of its mass (Table 1), showed that montmorillonite is the dominant clay mineral (Mohamed 2003). The wetted platy montmorillonitic clay tends to enhance slippage between the sand particles therefore causing reduction in the strength of the plastic silty sand. Thus strength reduction is more pronounced when the silty sand is dense and the silt fraction is less than 25% (Figure 3).
FIG. 3. Dry and wet peak shear strength versus fines content (p=100 kPa)

FIG. 4. Vertical displacement - horizontal displacement curves for dry pure sand at relative densities 30% & 79.4%

Volume Change during Shearing
Figure 4 shows the volume change of the pure dry sand during shearing. The dense and loose pure sand samples experienced compression (positive values) and then
dilation (negative values) on shearing. The volume change of the pure wet sand during shearing showed similar trend to dry pure sand.

On addition of fines, the volume change characteristics of the dry sand+silt mixtures did not show any remarkable difference when compared to the volume change characteristics of pure sand. The silt grains tend to behave similar to the sand particles when both are dry.

However, when wetted the loose silty sand (with up to 25% silt) compressed during shear whereas the dense mixtures showed compression and then dilated during shear. The wetted samples with sand plus 40% silt and 60% silt compressed during shear (Figure 5). The volume change behavior of the wetted sand plus 40% silt is similar to that of fine grained soils (sand+60% silt).

![Graph showing vertical displacement vs horizontal displacement for wet sand soil contains 40% fines at relative densities 30% & 79.4%](image)

**CONCLUSIONS**

This research was intended to study the effect of fines content and wetting on the drained strength of plastic silty sands. Intensive laboratory testing program was carried out to study the drained shear strength characteristics of dry and saturated “wetted” compacted plastic silty sands using the direct shear test. Clean Marwa sand was obtained from the bed of the Nile River and was mixed with different percentage of a plastic silty soil to achieve silty sands with 4%, 8%, 16%, 25% and 40% fines content. The test specimens were prepared dry in the shear box at two relative densities (30% and 79.4%, i.e. loose and dense states). They were sheared under 50 kPa, 100 kPa and 150 kPa vertical loads to failure and the test data was recorded. The shear tests were repeated and drained tests were performed under saturated or wetted conditions. The
shear stress versus displacement and vertical movement versus displacement relationships were plotted. The data was analyzed and evaluated for the effects of fines content and wetting on the peak strength and volume change characteristics of the sand-silt mixtures.

The dry silty sands, loose and dense, showed similar stress-displacement behavior up to 25% fines content and behaves like sand. Upon wetting the shear resistance dropped significantly causing decrease of the peak strength (up to 35%) which is more noticeable for low silt contents (up to 16%). A possible explanation is that, where the silt content is small, the montmorillonitic clay fraction within the silt caused slippage of the sand particles at their contact and consequently decrease in strength.

The volume change behavior during shear is the same for all the dry samples of sand-silt mixtures. The specimens experienced compression and then dilation, similar to the behavior of pure sand. However, the volume change behavior for all the wet samples of sand-silt mixtures depends on their silt content and relative density. For silt content up to 25%, the wetted loose siltry sands compressed during shear. However, for silt content up to 25%, the wetted dense silty sands showed compression and then dilation during shear. The wetted silty sands with 40% silt compressed during shear (for both loose and dense states) and behaved like fine grained soils.

REFERENCES

Mohamed E. A (2001) "Subsoil Analysis of Khartoum City" M.Sc. Thesis, Faculty of Engineering, University of Khartoum, Sudan