Measuring the Compressibility and Shear Strength of Conditioned Sand under Pressure
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ABSTRACT
Understanding the influence of soil conditioning parameters on soil behavior is critical to effective EPB TBM face support and performance. A mobile field lab has been developed to conduct various tests on conditioned muck sampled off the conveyor belt. A central piece to the field lab is measuring mechanical properties under pressure. This paper investigates conditioned soil behavior under pressure (up to 5 bar), and explores the influence of key soil parameter void ratio on behavior under pressure. Shear strength and compressibility tests were carried out on granular soil in a field-portable pressurized test chamber under a variety of pressures and foam parameters. The presented results demonstrate that void ratio, pressure and foam parameters all influence the performance of conditioned soil.

INTRODUCTION
Properly conditioned soil is required for optimal EPB performance (torque reduction, wear reduction, bulkhead pressure stability, and low permeability to prevent water inflow). Ideal soil conditioning reduces the shear strength, permeability and abrasivity of the formation soil while increasing its compressibility to provide stable face support. Within and across tunneling alignments, soil types and stress conditions can change subtly and/or significantly, yet for many of these cases, the injection and mixing of foam-based surfactants is routinely consistent. In-situ stress conditions can influence the behavior of conditioned soil considerably, yet the majority of conditioned soil testing is performed under atmospheric conditions.

This paper examines the behavior of conditioned soil under pressures ranging from 1-5 bar (gage pressure) that was examined using a pressurized testing chamber developed to be field portable. The paper will address the relationship between pressure, foam expansion ratio (FER) and foam injection ratio (FIR), the relationship between FER, FIR and the void ratio, and the relationship between the void ratio and engineering behavior, namely compressibility, elasticity and shear strength. The paper builds upon previous research that recognized the importance of the soil’s void ratio on its compressibility and shear strength (Bezuijen et al., 2005; Bezuijen et al., 1999; Bezuijen et al., 2006; Houlsby & Psomas, 2001; Maidl, 1995).

TEST METHOD AND PLAN
A pressurized testing chamber (PTC) is used to conduct the tests (Figure 1). The PTC is able to apply a total vertical stress up to 5 bar by mechanically compressing a calibrated load spring. The top platen can be lowered into the soil while recording its deformation. A 140 mm x 70 mm shear vane is used to determine the soil’s vane shear strength under pressure. The device (shown in Figure 1) is built to be used in the tunnel and does not require power or a pressurized air supply.
The compressed load spring provides a total vertical stress to the top of the sample $\sigma_{vt}$ per Equation (1):

$$\sigma_{vt} = \frac{(H_{S1} - H_{S2})k - F_f}{A}$$

where $H_{S1}$ and $H_{S2}$ are the initial and final spring heights, $k$ is the spring constant, $A$ is the area of the top platen and soil specimen, $F_f$ is the friction force between the sidewalls and the top platen.

The properties of the granular soil used in this study are listed in Table 1. For each test, dry soil mixed with 10% moisture (by weight) is thoroughly mixed with foam produced in an instrumented lab foam generator under atmospheric pressure. The PTC is filled with conditioned soil and the top platen is placed for load application. The atmospheric $FER_0$ and $FIR_0$ (subscript $p = 0$ indicates atmospheric or zero gage pressure) are determined by the liquid and air flow meters of the foam generator. During the mixing of soil with foam at atmospheric conditions additional air can be incorporated into the mixture and the $FER_0$ and therefore the $FIR_0$ will increase. The actual $FER_0$ and $FIR_0$ have been calculated for each test and will be reflected in the figures.
Table 1: Properties of the used soil.

<table>
<thead>
<tr>
<th>Soil Name</th>
<th>Soil Type</th>
<th>Gravel (%)</th>
<th>Sand (%)</th>
<th>Silt (%)</th>
<th>Clay (%)</th>
<th>PI</th>
<th>Moist density (g/cm³)</th>
<th>$\varepsilon_{\text{max}}$</th>
<th>$D_{50}$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil</td>
<td>Masonry sand with 10% silica powder</td>
<td>0</td>
<td>90</td>
<td>8</td>
<td>2</td>
<td>non plastic</td>
<td>2.12</td>
<td>0.59</td>
<td>0.6</td>
</tr>
</tbody>
</table>

Two test series were conducted with the soil. One test series examined the compressibility of the conditioned soil; the other examined the vane shear strength of the soil. The same $C_f = 5\%$ (surfactant concentration) and $FER_0$ were used for all types of tests. Both $FER_p$ and $FIR_p$ are pore pressure dependent values and the equations for $C_f$, $FER_p$, and $FIR_p$ are shown below.

\[
C_f = \frac{V_{\text{Surfactant}}}{V_{\text{Solution}}} \tag{2}
\]

\[
FER_0 = \frac{V_{\text{Foam}}}{V_{\text{Solution}}} \tag{3}
\]

\[
FIR_0 = \frac{V_{\text{Foam}}}{V_{\text{Soil}}} \tag{4}
\]

\[
FER_p = 1 + (FER_0 - 1) \frac{p_{\text{atm}}}{p + p_{\text{atm}}} \tag{5}
\]

\[
FIR_p = FIR_0 \frac{FER_p}{FER_0} \tag{6}
\]

where $p$ is the air gage pressure. All pressures in this paper are gage pressures. Equations (5) and (6) are plotted in Figure 2 to illustrate the decrease of $FER_p$ and $FIR_p$ with increasing pressure.
For each compressibility test the conditioned soil is transferred to the PTC and the compressibility top platen is placed on top of the soil. An air release port in the top platen is closed and the spring and the load reaction plate are positioned. The soil is then pressurized by lowering the reaction plate in prescribed increments to compress the calibrated load spring. Spring compression can be measured at each increment and the applied vertical force is calculated from this multiplied by the spring constant. The applied force minus the sidewall-platen friction force is averaged over the 156 mm diameter top platen to estimate the applied total vertical stress. The specimen in the chamber is not under a uniform stress state due to sidewall friction between the soil and the container. Therefore, the vertical stress at the bottom of the chamber as well as the lateral stress over the height of the specimen is not precisely known.

The test preparation procedure for the vane shear test is similar to the one for the compressibility test, only that the shear vane is lowered into the soil with a special top platen instead of the compressibility top platen. The soil is pressurized up to the final vertical stress and the vane shear strength is measured. Both the peak and residual vane shear strength are measured with a torque wrench, but only the peak vane shear strength is presented in this paper.

RESULTS

Relationship between Void Ratio and Compressibility

The first compressibility test presented in Figure 3 involved a sample with initial void ratio $e_0 = 1.4$ and $FIR_0 = 0.82$, compressed gradually from $\sigma_v = 0$ to 350 kPa (3.5 bar) and then gradually unloaded to $\sigma_v = 0$. During loading the vertical top platen compression $\delta$ increases monotonically and begins to plateau, reaching 60 mm at $\sigma_v = 350$ kPa. The compression of the void space reflects the contraction of the foam bubbles, decreasing the foam injection ratio from $FIR_0 = 0.82$ to $FIR_{3.5} = 0.25$.

The change in void ratio along with $FIR_p$ is shown in Figure 3b. The $e_{max}$ of the dry sand is shown in this plot for reference. Also shown in Figure 3 is the theoretical response of the sample assuming the...
deformation is attributed completely to air compression. The theoretical response for $\delta$ and $e$ are shown in Equations (7), (9), and (9),

$$\delta = \frac{V_{Air} \left( 1 - \frac{p_{atm}}{p_{atm} + p} \right)}{A}$$

(7)

$$n = 1 - \frac{M_d}{G_s \left[ V_0 - V_{Air} \left( 1 - \frac{p_{atm}}{p_{atm} + p} \right) \right]}$$

(8)

$$e = \frac{n}{1 - n}$$

(9)

where $V_{Air}$ is the volume of air in the conditioned soil at atmospheric conditions, $p_{atm}$ is the atmospheric pressure, $p$ is the present pore pressure, $M_d$ is the dry mass of soil used in the test, $G_s$ is the specific gravity of the soil, and $V_0$ is the total volume of the conditioned soil at atmospheric conditions.

Figure 3 shows that the conditioned soil response is controlled by air compression for $\sigma_{vt}$ up to 2 bar and for $e \geq 0.7$. The sand grains have no influence on behavior in this region; they are simply ‘along for the ride.’ As $e$ decreases below 0.7 and towards $e_{max}$, the sample response becomes less compressible than air. In this region, grain to grain contact begins to contribute to specimen response. During unloading, the specimen exhibits elastic behavior over the entire stress regime. This suggests that the contribution of grain to grain interaction for $\sigma_{vt} > 2$ was not significant and did not induce plastic response (permanent grain deformation).

The results of a second test involving an initially denser sample ($e_0 = 1.1, FIR_0 = 0.62$) is presented in Figure 4. Here, the sample exhibits the compression behavior of air until $\sigma_{vt} = 1$ bar, beyond which the soil grains interact and sample compressibility decreases. The void ratio at which the sample transitions from air compression behavior to grain to grain behavior is 0.7, similar to that observed in the first test. So while the total vertical stress at this transition point is different, 2 bar vs. 1 bar, the transitional void ratio is the same. Based on this limited data set, the transitional void ratio $e = 0.7$ ($e/e_{max} = 1.2$) appears an important parameter. The transitional stress magnitude will be a function of $e_0$, $FIR_0$ and $FER_0$.

The second test specimen also exhibits elastic behavior upon unloading. A comparison of the two specimens shows that they were each compressed to void ratios slightly greater than $e_{max}$ at $\sigma_{vt} = 3.5$ bar before unloading. Perhaps if they were loaded beyond 3.5 bar and $e < e_{max}$, they would exhibit elastic-plastic behavior. This requires further investigation.
Figure 3: Compression behavior of conditioned soil with $FIR_0$ of 0.82. Filled symbols are used for loading and open symbols are used for unloading. (a, top) Increase in compression and decrease of $FIR$ with increasing stress. (b, bottom) Decrease in void ratio and $FIR$ with increasing stress.
Figure 4: Compression behavior of conditioned soil with $FIR_0$ of 0.62. Filled symbols are used for loading and unfilled symbols are used for unloading. (a, top) Increase in compression and decrease of $FIR$ with increasing stress. (b, bottom) Decrease in void ratio and $FIR$ with increasing stress.
Figure 5: Comparison of compressibility $C$ for conditioned soil with $FIR_0=0.62$ and $FIR_0=0.82$.

Relationship between Void Ratio and Vane Shear Strength

The data shown in Figure 6 represents the vane shear test results of multiple tests with different $FIR_0$. The vane shear strength was tested at pressures ranging from 0 to 200 kPa. Figure 6 shows that at a void ratio above the transitional void ratio of $e=0.7$ the vane shear strength of the conditioned soil is in the range between 0 and 5 kPa. The results are independent of the $FER_0$ and the stress at which the measurement was taken. As the grain to grain contact begins to govern the behavior, the vane shear strength increases between the transitional and the maximum void ratio of the soil. Figure 7 shows that the vane shear strength increases with applied vertical stress when the void ratio is below the transitional void ratio of $e=0.7$. It is worth noting that the effective stress is not precisely known; however, it is assumed that the effective stress is increasing as $e$ decreases and that this is the root cause for the increase in vane shear strength.

Figure 6: Relationship between void ratio and vane shear strength. Maximum dry and transitional void ratios of the soil are also shown in plot.
CONCLUSIONS
The void ratio of \( e = 0.7 \) (\( e/e_{\text{max}} = 1.2 \)) was found to be a transitional point where the behavior of the conditioned soil changes from air compression behavior to grain to grain behavior. Above this transitional void ratio the behavior of the soil is governed by the foam bubbles. Between the transitional void ratio and the maximum dry void ratio the soil grain to grain contact starts to govern the behavior until full contact is reached at \( e_{\text{max}} \). The stress at the transition point is a function of the soil conditioning parameters \( FER_0 \) and \( FIR_0 \) and the grain size distribution of the soil. It is not known if the ratio \( e/e_{\text{max}} \) is soil specific. Further testing over a variety of soils is needed.

Vane shear test results under pressure show that at void ratios above the transitional void ratio, the vane shear strength is independent of applied total stress and ranges from 0 to 5 kPa for the tested soil. The vane shear strength then increases significantly from the transitional void ratio towards the maximum void ratio.

The results shed light on the relationship between pressure, conditioning parameters, and soil behavior. Ideal behavior is reached for \( e/e_{\text{max}} > 1.2 \) (for this soil). They show that compressibility and vane shear strength both depend on the void ratio of the conditioned soil. It was shown that the maximum void ratio of the soil, which depends on the grain size distribution of the soil, must be considered when designing the soil conditioning parameters.

REFERENCES

