A FEASIBILITY STUDY ON GRAVELLY SOIL CHARACTERIZATION VIA CENTRIFUGE TESTING

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Section 1. ABSTRACT

The focus of this study is to characterize five gravelly soils via index testing prior to performing Cone Penetration Tests (CPT) on the 1m radius centrifuge at the UC Davis Center for Geotechnical Modelling. By effectively characterizing the soil via index testing, the centrifuge tests can be used to determine the effects of gravel on CPT results and the soil's liquefaction potential. Procedures have to be developed in order to prepare the centrifuge models to a target relative density. This was done by performing a series of e_{max}, e_{min}, and dry density tests. The result of this study concluded in successful index characterization of the gravelly soils.

Section 2. INTRODUCTION

The Cone Penetration Test (CPT) is an important in-situ testing device used to assess the stratigraphy and geotechnical properties of soil. The design of the CPT helps obtain the strength profile as such: the conical tip measures resistance of the soil as it gets pushed into the ground, the sleeve reads out the horizontal friction of the soil, and sensors attached near the cone tip provide porewater pressure readings (Rogers). Although CPT tests are favorable as they can be performed on site at a low price, the benefit to performing centrifuge tests allows for control over variables of interest as the soil is created in a lab setting. Furthermore, by including a CPT in the centrifuge, it becomes easy to check for repeatability and uniformity of the soil whilst also measuring its continuous strength profile (Bolton et al., 1999).

A drawback to current CPT tests comes in the lack of accuracy when measuring profiles for gravelly soils. In the case of gravelly soils, an important parameter to consider is the particle to probe ratio; if the particle's diameter is as big or bigger than the probe diameter, the readings obtained for tip resistance will likely be interpreted in a way that would characterize the soil layer as being stronger than its true strength.

Bolton et al. (1999) conducted research to determine how large particles effect CPT results. This data was provided by EPIC, the European Programme of Improvement in Centrifuging, and the soil that was used by all centers was uniform Fontainebleau sand. Variables such as the shape and size of the mold and the type of pluviation performed were compared. The primary conclusion was that the cone diameter had to be 20 times greater than the mean particle diameter (D_{50}) so as to produce unbiased results (Bolton et al., 1999).

Because Bolton et al. (1999) draw their results from uniform Fontainebleau soil, his conclusions only hold true for uniformly graded soils. With regards to gap graded gravelly soils, the question of identifying particle influence on CPTs remains unanswered. By testing five different soils, amongst which some were well-graded and others gap-graded, this study aims to provide an insight into understanding gravel particle influence on CPT results. Figure 1 shows a theoretical representation of the diameter spectrum of the soils to be tested: the two outer curves represent uniform soils that will act as boundary layers- these two uniform soils were chosen because NJ#3 has the biggest particle-diameter so it will be used as a gravelly soil and NJ#70 has a smaller diameter so it will be used as a sandy soil; the next two inner curves represent gap graded soils- "15%G-85%S" and "40%G-60%S" indicate different percentages of gravelly and sandy soils used to make each distinct soil; and the linear, inner curve represents a well graded soil- this soil is composed of an even 25% amount of gravelly and sandy soils and those in between. Because these soils are composed of different sized particles, the results obtained will offer a range of results that will allow for better understanding of where CPT results become influenced by particle sizes.

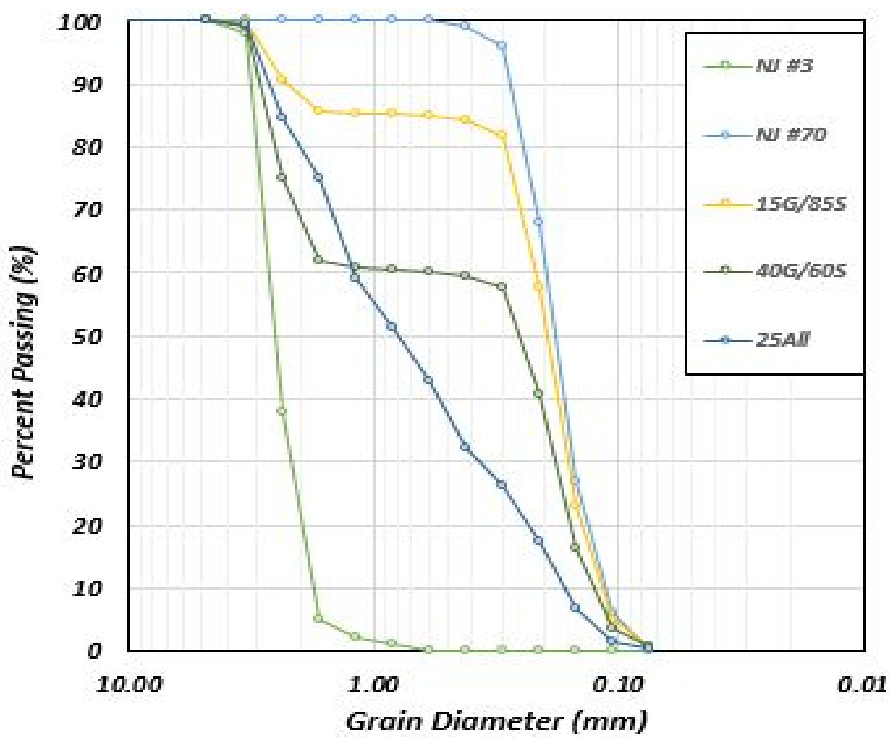


Figure 1: Grain-Size Distributions for Uniform and Mixed Soils

Relative density is a key parameter which controls CPT tip resistance (Jamiolkowski et al., 1985); therefore, it is important to effectively characterize the soil before performing a centrifuge test. As shown in Equation 1, relative density is a function of maximum and minimum void ratios so this study's focus will be on obtaining the necessary maximum and minimum dry density values for all five soils and then converting them to their respective void ratios via equation 1 for appropriate index characterization.

$$D_R = \frac{e_{max} - e}{e_{max} - e_{min}} \times 100\% \qquad \text{(Equation 1)}$$

Section 3. METHODS

From equation 1, the maximum, minimum, and in place void ratios must be obtained prior to determining the relative density of a soil. The procedures used to index the soils were from the American Society for Testing and Materials (ASTMS) and these were performed at the Center for Geotechnical Modeling at the University of California, Davis (CGM) as well as the Bryte Soils Lab - California Department of Water Resources (DWR). What follows is an outline summarizing the procedures.

Section 3.1 Obtaining Accurate Representations of Soil Samples for each Test

The first step to indexing the mixed soils was to obtain accurate representations of the soils to be tested. Obtaining substantial amounts of soil required the use of a splitter seen in Figure 1 (left) and Figure 1 (right) shows the basis for the number of splits performed on the initial 76 lbs.

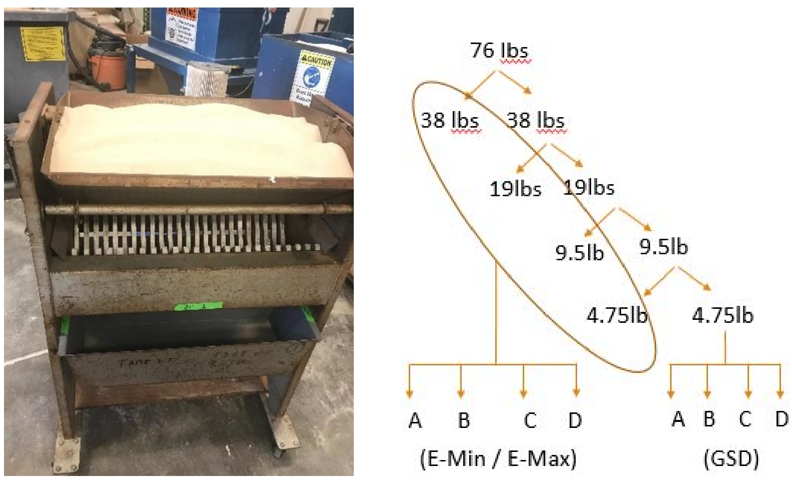


Figure 1: Bin Splitter Used (left) and Splitting Schematic (Right)

Although obtaining accurate amounts of uniform soil was not an issue, for mixed soils it was important to ensure there was enough gravelly material and fined sands to meet the specified mix percentages. To avoid using inaccurate samples for the mixed soils, an electric mixer was used.

To validate that the soil was thoroughly mixed and the samples were accurate representations, about 4 lbs of the initial 76 lbs of soil were used to conduct four g sieve analyses. Since the mixed soils were composed of uniform soils, the grain size distribution was theoretically supposed to fall within the boundaries of the uniform soils and performing this test would also allow for Figure 1 to be validated.

Section 3.2 E_{min} Testing

The minimum void ratio (e_{min}) of the five soils was found via ASTM D4253-16. Because the CGM did not have the required vibratory table required by the ASTM, this step was performed at the California Dept. of Water Resources (DWR), located in West Sacramento, CA. Although the ASTM provides 4 different methods for obtaining the minimum void ratio- 2 dry and 2 wet- the method used was the wet method as the dry method gave results that were looser as shown in Figure 11. This process began with an alternating step of putting soil inside the mold and then adding water via the use of a sponge as the vibratory table was set to its lowest setting. Once soil covered the top of mold and the table turned off, excess soil was removed and a surcharge plate, weight and sleeve were placed on top of the mold. A straight edge was used to trim off any excess soil. Figure 2 shows the process of setting up the mold prior to vibration (left) as well as the dial used to take rim and plate readings (right).

Figure 2: Setup of Equipment for E_{min} Testing

Rim and Plate readings were taken both before and after vibration occurred for the second time at a higher setting. Figure 3 shows the subsequent drying process.

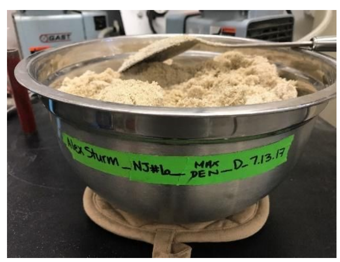


Figure 3: Drying Wet Soil to Obtain Mass of Soil

The rim and plate readings were used to calculate the volume of the soil via Equations 2 and 3 and drying of the wet soil led to obtaining the mass of the soil.

$$H_{soil} = H_{mold} - (R_{f,\,plate} - R_{f,\,rim} + T_{plate}) \qquad \text{(Equation 2)}$$

$$V_{soil} = V_{calibrated\ mold} - (A_{calibrated\ area\ of\ mold} \times H_{soil} \times Conversion\ Factor) \quad \text{(Equation 3)}$$

Performing this test led to obtaining ρ_{max}, Equation 4, which was then converted to e_{min} via Equation 5, where a specific gravity, G_s of 2.65 was assumed. For a more detailed process of this step, refer to ASTM D4253-16.

$$\rho_{dmax,\,n} = \frac{M_{dry\ soil}}{V_{soil}} \qquad \text{(Equation 4)}$$

$$e_{min} = \frac{\rho_w \times G_s}{\rho_{dmax,\,n}} - 1 \qquad \text{(Equation 5)}$$

Section 3.3 E_{max} Testing

The maximum void ratio (e_{max}) of the five soils was found via ASTM D4254-16. Although this method provided 3 different methods to use, for consistency and comparison purposes, Methods A and C were carried out.

Method A required the use of a mold and funnel (Figure 4, left). By pouring the soil through a funnel and keeping the funnel 0.5 in above the top of the soil sample, the soil was being placed within the mold at a loose state so the method yielded a minimum density (Figure 4, right).

Figure 4: Equipment (Left) and Soil Sample Tested (Right) for Method A

Method C required the use of a 2000 mL graduated cylinder. The method was carried out by filling the cylinder with 1000±1g of soil, placing it inside the cylinder, closing the top, inverting the cylinder, and reading the volume the soil took up (Figure 5). Equation 6 was then used to calculated ρ_{min} with Equation 7 converting this to e_{max}, where a G_s of 2.65 was used again.

Figure 5: Cylinder with Soil Sample Inside

$$\rho_{dmin,\,n} = \frac{M_{soil}}{V} \qquad \text{(Equation 6)}$$

$$e_{max} = \frac{\rho_w \times G_s}{\rho_{dmin,\,n}} - 1 \qquad \text{(Equation 7)}$$

Fragaszy et al. (1990) indicated how oversized particles had an effect of the density of a soil and P. Tang & V.M. Puri (2004) work suggested methods to avoid segregation when mixing soils (Youd 1973), it was important to ensure the soil appeared thoroughly mixed when performing Method C. Whilst uniform soil required only one inversion, mixed soil had to be inverted several times until thorough consistency was achieved.

The values obtained from Methods A and C were compared for consistency purposes.

Section 3.4 Pluviation

Pluviation was carried out to obtain the density of the soil. By using a mold with known volume, soil was dropped at different heights and flow rates from a rotating drum (Figure 6).

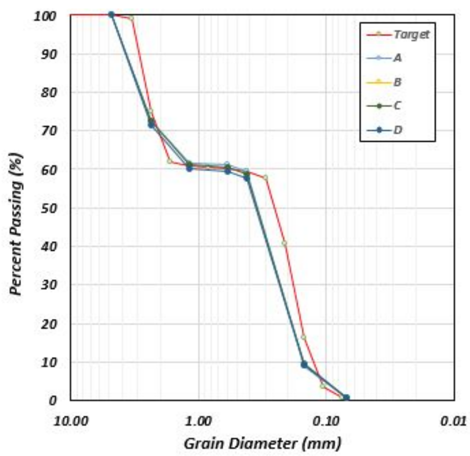
Figure 6: Rotating Drum and Pluviation Set-up

Four lifts of equal thickness, marked within the mold, were used: the first drop-height was 30 cm and once the soil reached a quarter of the mold's volume, the drum was raised such that the height difference between the top of the soil surface and drum was again 30 cm. This was repeated until the mold was completely full. Because the volume of the mold was known, the density was calculated using Equation 8:

$$\rho = \frac{M_{soil}}{V_{mold}} \qquad \text{(Equation 8)}$$

Section 4: RESULTS & DISCUSSION

The focus of this study was to use index testing to characterize gravelly soils for centrifuge testing. Because three of the samples were mixed soils and two were uniform, Figure 1 showed a theoretical representation of what was expected to be achieved in terms of the soil's particle-diameter ranges. Figures 7 through 9 show the grain size distribution curves (GSD) for the mixed soils: Figure 7 shows the GSD for the gap-graded, 40%G-60%S soil, Figure 8 shows the gap-graded, 15%G-85%S soil, and Figure 9 shows the well-graded, 25%All soil. In all three figures, the red lines represent the target soil gradation curves for the mixed soils. Although slight variations are observed within each figure, the experimental GSD curves are within range of the theoretical target curve, thus indicating that the prepared soils are decent representations of the gravelly soils for purposes of this study.



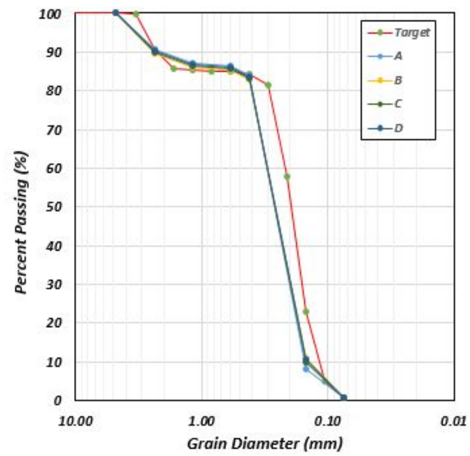


Figure 7: GSD for 40% Gravel, 60%Sands

Figure 8: GSD for 15% Gravel, 85%Sands

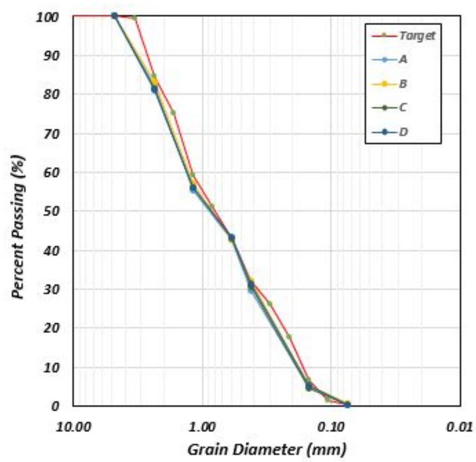


Figure 9: GSD for 25% All

Once the different samples for all soils were validated as being accurate representations of the mixed soils through the GSD curves, e_{min}, e_{max}, and pluviation was carried out. Table 1 and Table 2 show recorded measurements that were used to obtain the e_{min} of one of the gap graded soil samples- the 15%G-85%S, Sample A soil via the wet method as specified in ASTM D4253-16. Table 1 shows the rim and plate readings recorded at DWR lab and Table 2 shows the mass readings taken during the drying process for Sample A of the 15%G-85%S mixed soil.

Table 1: Rim and Plate Readings

Trial	R_i	R_f
(-)	(in)	(in)
1	1.21	1.48
2	1.21	1.48
3	1.21	1.49
4	1.21	1.48
Avg	1.21	1.48

Table 2: Mass of Oven-Dry Soil Sample

Trial	Day	Time	Temp	$M_{bowl+soil}$	M_{soil}	% Diff
(-)	(-)	(-)	(°F)	(lbm)	(lbm)	(%)
1	0	11:00 AM	215	13.22	12.51	
2	3	2:17 PM	205	10.82	10.11	19.2
3	4	10:15 AM	210	10.82	10.11	0.0

By use of Equations 2 through 5, the maximum density for all soil samples were obtained and then converted to minimum void ratios. Figure 10 shows the minimum void ratios obtained for each sample of the 15%G-85%S gap-graded soil.

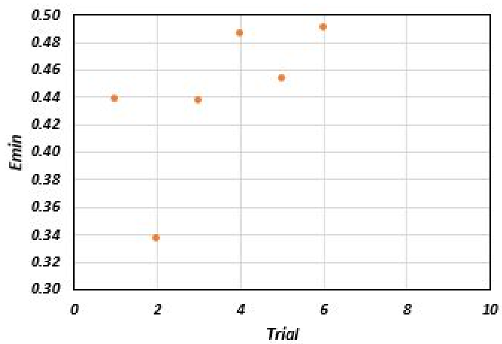


Figure 10: Emin values for 15%G-85%S Soil

Although the plot of e_{min} vs trials shows a scatter, the e_{min} value used for relative density was 0.42, which was obtained by averaging the e_{min} of all sample trials for that soil.

In an effort to compare the wet and dry methods specified by ASTM D4253-16, Figure 11 shows the rim and plate readings as well as the volume and weight of the soil for each.

Sample D (DRY)				Sample D (WET)			
Dial Readings				Dial Readings			
Rim		Plate		Rim		Plate	
Initial	Final	Initial	Final	Initial	Final	Initial	Final
1.162	1.163	1.287	1.211	1.163	1.170	1.390	1.385
1.163	1.164	1.321	1.207	1.164	1.171	1.411	1.400
1.161	1.164	1.380	1.182	1.158	1.170	1.422	1.305
1.161	1.163	1.357	1.183	1.163	1.169	1.398	1.289
Average	1.164	average	1.196	Average	1.170	average	1.345
Vs (ft3) =		0.089547662		Vs (ft3) =		0.087216012	
Wdry soil (lb) =		9.055		Wwet soil (lb) =		11.7215	

Figure 11: Comparison in Data Collected for Wet and Dry Method

By comparison, it can be seen that the dry method produces a lower mass for soil and since density is a function of mass over volume, the density of the dry soil will be lower than the density of the wet soil. Through conversion, this will in turn result in a higher and loose void ratio than for the wet method.

The purpose of having used two methods to determine the maximum void ratio-or minimum density- was to ensure there was consistency in the methods and their respective values. Figure 12 shows a comparison between Method A and Method C. The numbers are consistent throughout both methods, but for purposes of timing and efficiency, Method C was used to perform the rest of e_{max} testing.

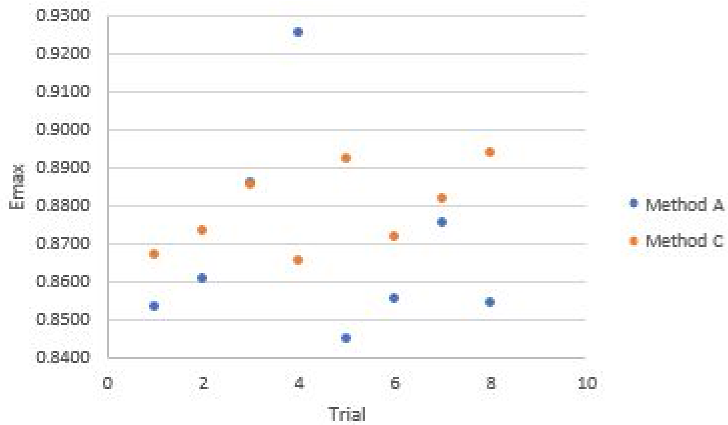


Figure 12: Comparison between Method A and C for E_{max} Testing

Pluviation was used to obtain the in-situ density, which would then be used to finalize the relative density calculation from Equation 1. Because this study focuses on mixed gravelly soils, the sieve method was not an option as this would lead to segregation of particles. The use of a rotating drum was effective as this minimized the issue of segregation. Table 3 illustrates the densities that were achieved at different drop heights and flow rates for a well-graded mixed soil, labeled 25%All.

Table 3: Pluviation Results and Calculated Relative Density for 25%All Soil

H	V	Drum	Lifts	Trial	M_{soil}	ρ	e	D_R
(cm)	*(-)*	*(-)*	*(-)*	*(-)*	*(kg)*	*(lbf/ft^3)*	*(-)*	*(%)*
40	10	5mm	3	1	25.01	114.24	0.447	38.25%
40	10	5mm	3	2	25.07	114.51	0.444	39.93%
40	10	5mm	3	3	25.1	114.65	0.442	40.77%
40	8	5mm	3	1	25.175	114.99	0.438	42.86%
40	8	5mm	3	2	25.05	114.42	0.445	39.37%
40	8	5mm	3	3	25.01	114.24	0.447	38.25%
40	4	5mm	3	1	25.27	115.43	0.433	45.49%
40	4	5mm	3	2	25.22	115.20	0.435	44.11%
40	4	5mm	3	3	25.27	115.43	0.433	45.49%

The last column in Table 3 demonstrates the calculated relative density values via Equation 1. By running three different trials for each drop height at the same height and plotting their corresponding relative densities, a relative density curve can be drawn for a soil using the average values at each drop height. Once this curve is plotted as seen in Figure 13, a target relative density can be specified; the blue line is the relative density curve for well-graded, 25%All soil at a drop height of 40 cm. If a relative density of 43% was targeted, this could be obtained by determining what its corresponding flow rate is as well as the drop height needed to achieve this.

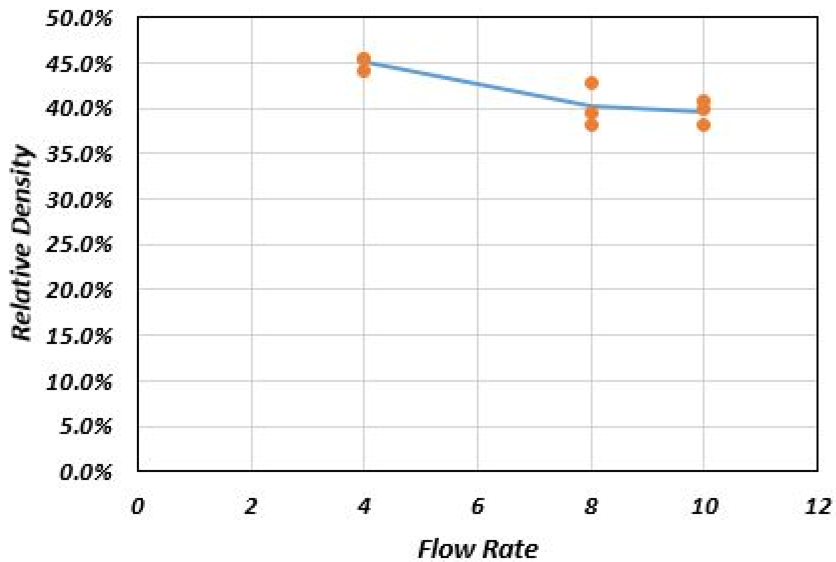


Figure 13: Flow Rate vs Relative Density Curves

After completing all index testing, Tables 4 and 5 highlight the minimum and maximum void ratios and densities. Table 4 shows the results for the uniform soils used while Table 5 shows the results for the two gap graded and well graded soils. With these values, pluviation will be carried out to obtain the relative density curves for all soils to then perform centrifuge testing.

Table 4: Uniform Soils Characteristics

Soil		NJ#3	NJ#1	NJ#6	NJ#70
$\rho_{max,avg}$	(lbm/ft^3)	110.332	100.296	102.666	105.835
$e_{min,avg}$	(-)	0.508	0.650	0.615	0.563
$\rho_{min(C),avg}$	(lbm/ft^3)	88.028	88.295	89.524	88.015
$e_{max(C),avg}$	(-)	0.879	0.873	0.847	0.879

Table 5: Mixed Soils Characteristics

Soil		15%G-85%S	25%-All	40%G-60%S
$\rho_{max,avg}$	(lbm/ft^3)	116.255	125.280	123.079
$e_{min,avg}$	(-)	0.425	0.321	0.344
$\rho_{min(C),avg}$	(lbm/ft^3)	94.176	108.364	105.810
$e_{max(C),avg}$	(-)	0.756	0.526	0.563

Section 5: CONCLUSION

Through use of ASTMs D4253-16 and D4254-16, the minimum and maximum void ratios were obtained and pluviation of the soil led to obtaining the density of the soil. By use of Equation 1, soil characterization for mixed, gravelly soils was further achieved. Because this study only focused on characterizing the soil, the next step will be to perform centrifuge testing to determine if Bolton's results hold true for mixed soils and whether there are other parameters that affect CPT testing results.

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