Pore Pressure Generation of Pea Gravel, Sand, and Gravel-Sand Mixtures in Constant Volume Simple Shear

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ABSTRACT
The generation of pore pressures in soils during earthquake loading is important to understand for designing earthquake resistant structures. Pore pressure generation of sands and sand-silt mixtures has been investigated, however less data is available for gravelly soils. A large-size cyclic simple shear (CSS) device was utilized in this study to perform constant volume cyclic simple shear tests of Pea Gravel, Ottawa C109 sand, and mixtures of the two (80% sand, 60% sand, and 40% sand). In particular, the generation of pore pressures during each test was investigated to understand the response of gravelly soils during earthquake loading conditions. The initial vertical effective stress applied to each specimen ranged between 100 and 400 kPa. Specimens were prepared at two relative densities: loose (47%) and dense (87%). Results from the CSS liquefaction tests were compared to existing pore pressure generation models from the literature to highlight the different behavior of gravels compared to sands. Results show that relative density is an important parameter in the generation of excess pore pressure for gravel and gravel-sand mixtures. The gradation characteristics of the gravel is shown to have a significant effect on pore pressure generation, with well-graded gravelly soils showing higher pore pressure generation in the first few cycles of testing compared to poorly-graded gravels. Gravel and gravel-sand mixtures tested in this study displayed pore pressure generation similar to the gravelly soils tested by Evans and Seed (1987).

1 INTRODUCTION

In soil liquefaction analysis, it is critical to understand the generation and dissipation of excess pore pressures. During undrained loading, excess pore pressures develop due to shearing, which causes a reduction in effective confining stress and therefore a loss in soil stiffness. Many researchers have studied this response in sands (Lee and Albaisa, 1974; DeAlba et al., 1975; Martin et al., 1975; Seed et al., 1975; Dobry et al., 1982; Kammerer et al., 2004; Wu et al., 2004) and silt and sand-silt mixtures (Green et al., 2000; Polito and Martin, 2001; Polito et al., 2008), but limited data is available for gravelly soils (Evans and Seed, 1987; Haeri and Shakeri, 2010; Banerjee et al., 1979; Hynes, 1998).

Various models have been developed to predict excess pore pressure generation. Seed et al. (1975) developed a stress-based model using data from undrained, stress-controlled cyclic tests on sand. An empirical model for the pore pressure ratio, r_u (u/σ_{v0}') in Equation 1, was developed using the relationship between excess pore pressure generation (r_u) and the cyclic ratio (N/N_L), which is the number of cycles normalized by the number of cycles to liquefaction.

$$r_u = \frac{1}{2} + \frac{1}{\pi}\arcsin(2 * \left(\frac{N}{N_l}\right)^{1/\alpha} - 1) \qquad [1]$$

where α is an empirical constant that is a function of the soil properties and test conditions. A best fit for the sand data in Seed et al. (1975) was found using an α value of 0.70. Other researchers have since developed models that are stress-based (Polito et al., 2008), strain-based (Martin et al., 1975; Dobry et al., 1985), or energy-based (Green et al., 2000).

These models have all been developed using sand and silty soils. The pore pressure generation of gravels and gravelly soils has been less extensively studied due to the unavailability of large-size laboratory devices that can accurately capture pore pressure generation. Moreover, many of the existing laboratory studies on gravelly soils have utilized triaxial testing devices, which are susceptible to membrane compliance effects. Several studies (Evans and Seed, 1987; Haeri and Shakeri, 2010) have assessed the effects of membrane compliance on pore pressure generation and developed corrections; however, there is not an agreed upon method for these corrections. Banerjee et al. (1979) tested well-graded Oroville gravel with a maximum particle size of 2" using a large-size triaxial apparatus and found gravel pore pressure generation increase to be different from that of sands. The excess pore pressure generation for gravels increased rapidly in the first few cycles and then slowly in the following cycles. These results agreed with previous tests of well-graded Oroville gravel tested by Wong et al. (1974). Evans and Seed (1987) tested gravel in a large-size triaxial apparatus (307 mm diameter) and a smaller-size triaxial apparatus (71 mm diameter) and sluiced specimens with sand to minimize membrane compliance. Non-compliant (unsluiced) specimens were found to have higher cyclic resistance by 55% and different pore pressure response than the sluiced specimens and previous sand results. Sluiced specimens, which were noted to more accurately represent "true" response, generated excess pore pressures greater than sands and near the upper bound of the Lee and Albaisa (1974) data for sand. Hynes (1988) tested Folsom gravel in a large-size triaxial apparatus and found pore pressure generation at cyclic shear strain levels of 1% to be independent of initial confining stress, relative density, overconsolidation ratio, and anisotropic consolidation conditions. Chang et al. (2014) presented cyclic simple

Table 1. Characteristics of tested soils.

Characteristics	Pea Gravel	60%Gravel 40% Sand	40% Gravel 60% Sand	20% Gravel 80% Sand	Ottawa C109 Sand
G_S	2.74	2.70	2.69	2.67	2.65
$\Upsilon_{d,max}$ (kg/m^3)	1741	2114	1978	1848	1733
$\Upsilon_{d,minn}$ (kg/m^3)	1546	1960	1818	1665	1512
e_{max}	0.772	0.379	0.477	0.602	0.752
e_{min}	0.574	0.279	0.358	0.443	0.529

shear data for the liquefaction response of gap-graded gravelly soils and found pore pressure generation to be similar or below that of sands. Increasing gravel content was shown to increase pore pressure generation.

In this study, a large-size cyclic simple shear (CSS) device was utilized to perform cyclic tests of gravel, sand, and gravel-sand mixtures, with an emphasis on assessing the effects of initial vertical effective stress, relative density, and mixture percentage on the generation of excess pore water pressure.

2 TEST MATERIALS AND PROCEDURES

The materials used in this study were Pea Gravel and Ottawa C109 sand. Pea Gravel is a rounded to sub-rounded gravel with a D_{50} of approximately 9 mm, while Ottawa C109 sand is a rounded to sub-rounded sand with a D_{50} of approximately 0.35 mm. Table 1 summarizes the material properties of Pea Gravel and Ottawa C109 sand, as well as mixtures with varying percentages of these two materials. To test the effect of gravel and sand content on pore pressure generation, mixtures of Pea Gravel and Ottawa C109 sand were mixed by percent weight. Mixtures of 80% sand, 60% sand, and 40% sand were prepared and tested. The grain size distributions for all test materials are shown in Figure 1. The grain size distribution for Pea Gravel was evaluated using the Translucent Segregation Table (Ohm and Hryciw, 2013), while the Ottawa C109 sand and gravel-sand mixture distributions were evaluated using ASTM D6913. Minimum and maximum densities for Pea Gravel and Ottawa C109 sand were determined using ASTM D4254. However, using a vibratory table for determining maximum density for the gravel-sand mixtures resulted in particle segregation and values of maximum density that were biased low. Therefore, an alternative method for determining maximum density was used and validated by comparing with results from prediction equations developed by Fragaszy and Sneider (1991). The same mold used for the Pea Gravel and Ottawa C109 sand (in accordance with ASTM D4254) was used. The method of obtaining maximum density consisted of placing the gravel-sand mixtures in approximately 25 mm layers, tamping with a rubber mallet 25 times, and applying approximately 100 rapid surface tamps to the gravel-sand mixture using a small cylinder. This method resulted in values of maximum density that compared very well with results by Fragaszy and Sneider (1991). In addition, this method compared well with ASTM D4254 for the 80% sand/20% gravel specimen where particle segregation was not evident.

The large-size CSS device used in this study, utilizes circular stacked rings (307 mm in diameter) to laterally confine specimens and enable testing at K_0 conditions (Hubler et al., 2014; Hubler et al., 2017). A latex membrane was placed inside the rings as a cushion to prevent damage to the rings. Specimens were prepared at two relative densities, D_r = 47% and D_r = 87%. For Pea Gravel, D_r = 47% specimens were prepared by placing particles loosely in dry conditions with a small shovel. For gravel-sand mixtures and Ottawa C109 sand, D_r = 47% specimens were prepared using dry pluviation (a funnel with zero drop height) and slight tamping with a rubber mallet, if needed. For D_r = 87% specimens, a circular (diameter = 150 mm) weight of 5.5 kg was dropped from a height of 50-75 mm. For Pea Gravel and Ottawa C109 sand, the weight was dropped 25 times in 3 equal layers, while for the gravel-sand mixtures, the weight was dropped 30-50 times in 5 equal layers. A greater number of drops was used for successive layers to ensure specimen uniformity.

Test specimens were first consolidated to the desired initial vertical stress and then cyclically sheared under stress-controlled conditions at a specific cyclic stress ratio (CSR). In this testing program, a CSR of 0.094 was used for all cyclic tests. Testing was completed under constant volume conditions, which has been shown to be equivalent to undrained conditions in cyclic simple shear testing (Dyvik et al. 1987). Pore pressure generation throughout the test was calculated using the difference in vertical stress measured on the top cap (top of the specimen) of the CSS device compared to the initial vertical stress (vertical stress at the end of consolidation and prior to shearing).

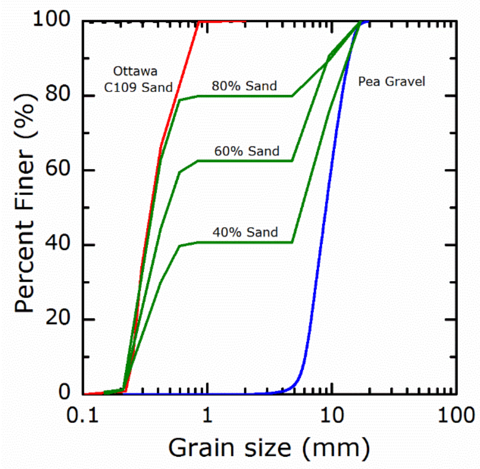

Figure 1. Grain Size Distribution of Tested Material

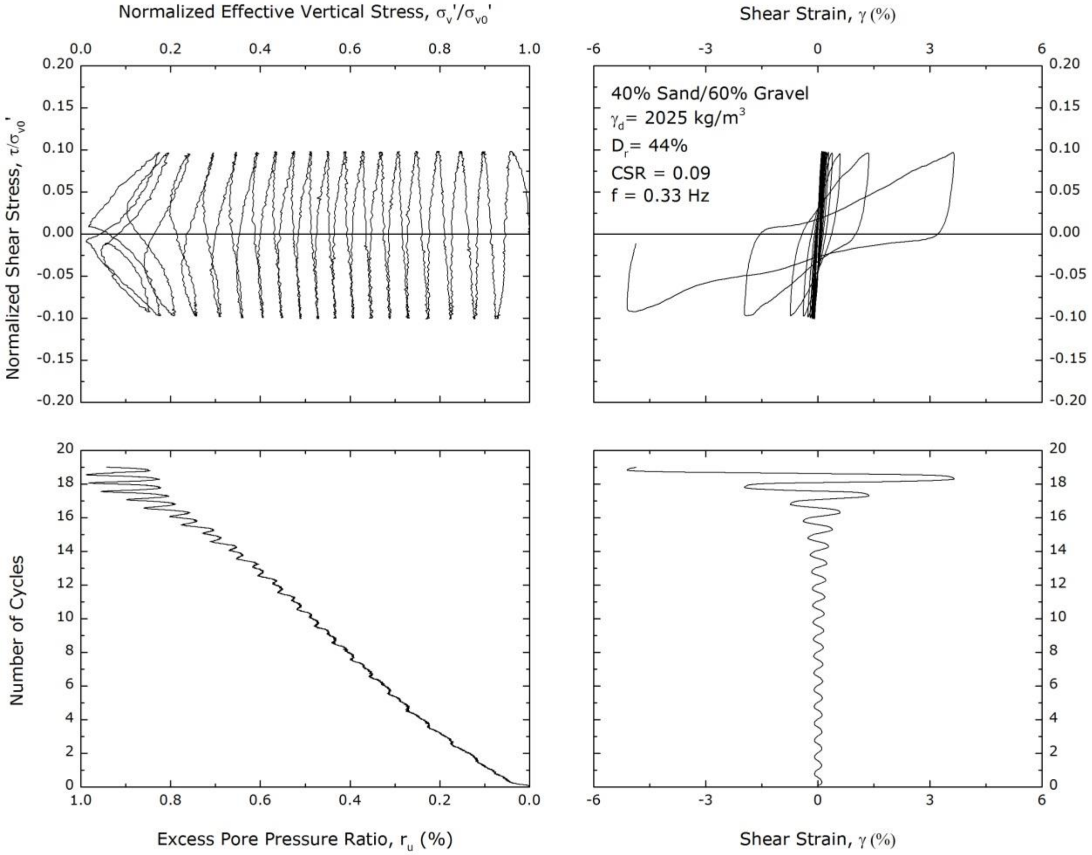

Figure 2. Example cyclic data for 40% Ottawa C109 sand/60% Pea Gravel specimen at CSR = 0.09 and σ_{v0}' = 100 kPa

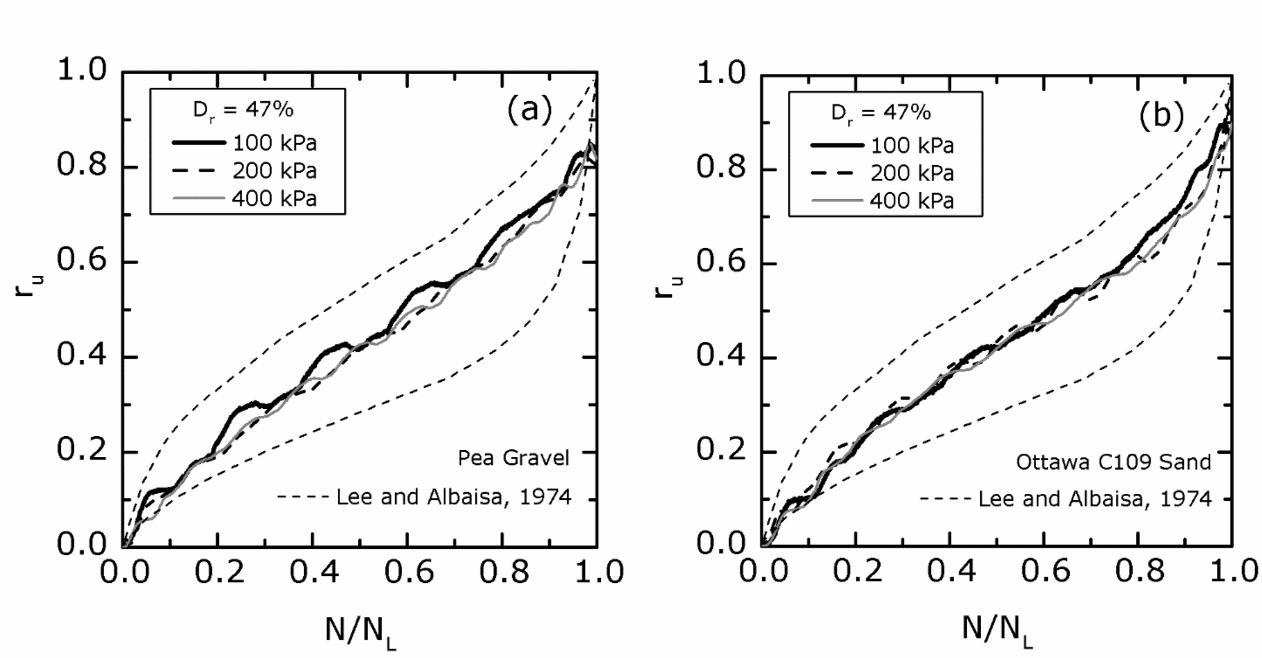

Figure 3. Effect of Initial Vertical Stress on Pore Pressure Generation for (a) Pea Gravel and (b) Ottawa C109 Sand

3 TEST RESULTS

Tests were conducted for specimens of Pea Gravel, Ottawa C109 sand, and gravel-sand mixtures. Example CSS data for a mixture of 40% Ottawa C109 sand and 60% Pea Gravel is shown in Figure 2. Initial vertical effective stress, relative density, and mixture percentage were varied for the tests so that the effect of these parameters on pore pressure generation during cyclic loading could be investigated. Pore pressure generation is presented by plotting the residual excess pore pressure ratio ($r_u = u/\sigma_{v0}'$) versus the cycle number normalized by the number of cycles to liquefaction of a specimen during cyclic testing. This plot is a common plot used for comparison of pore pressure generation (Seed et al., 1975). In each plot, the lower and upper bounds for sand (Lee and Albaisa, 1974) are shown for comparison. Liquefaction, in this study, is assumed to occur when a 3.75% single amplitude shear strain is measured during cyclic simple shear testing. This criterion for liquefaction has been used in previous studies utilizing cyclic simple shear devices (Vaid and Sivathayalan, 1996).

3.1 Effect of Initial Vertical Stress

The effect of initial vertical effective stress (σ_{v0}') was investigated by comparing results for specimens of Pea Gravel and Ottawa C109 sand at σ_{v0}' = 100, 200, and 400 kPa as shown in Figure 3. The test results show that there is little to no effect of σ_{v0}' on the pore pressure generation for Pea Gravel and Ottawa C109 sand at a D_r = 47%. The data falls approximately in the mid-range of Lee and Albaisa (1974). Figure 3a also shows that Pea Gravel pore pressure generation at D_r = 47% is very similar to the Ottawa C109 sand at D_r = 47% in Figure 3b.

The data for Pea Gravel and Ottawa C109 sand is nearly the same, except at N/N_L greater than 0.80. After this point, the Ottawa C109 sand develops pore pressures rapidly and reaches r_u values close to 1, while the Pea Gravel r_u does not increase rapidly and instead stays fairly linear. The Pea Gravel test specimens reach r_u values of approximately 0.80-0.85 when N/N_L = 1. Thus, Pea Gravel reaches the liquefaction strain criterion of 3.75% shear strain at lower values of r_u than Ottawa C109 sand.

3.2 Effect of Relative Density

The effect of relative density (D_r) was compared for specimens of Pea Gravel and Ottawa C109 sand at σ_{v0}' = 100 kPa as shown in Figure 4. The test results show that for Pea Gravel, D_r has a significant effect. For Pea Gravel, an increase in D_r from 47% to 87% shifted the excess pore pressure line upward near the upper bound of the Lee and Albaisa (1974) data for sands. For Ottawa C109 Sand, the excess pore pressure lines are similar for the two different relative densities, with slight differences for N/N_L less than 0.25 and greater than 0.75. It should be noted that the D_r = 87% specimen took many cycles to liquefy (183 cycles).

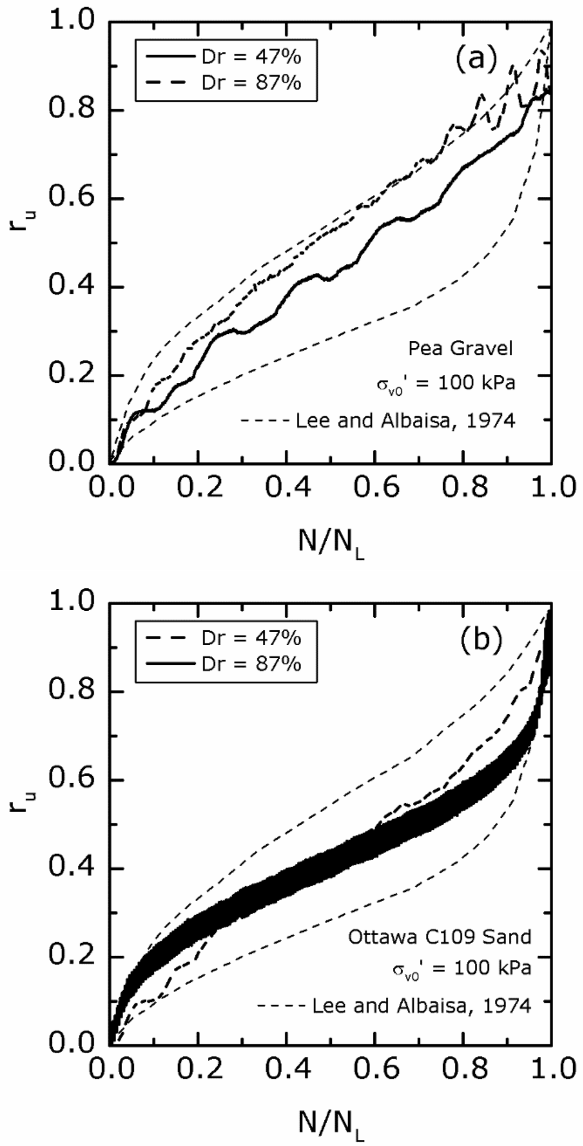

Figure 4. Effect of Relative Density on Pore Pressure Generation for (a) Pea Gravel and (b) Ottawa C109 Sand

3.3 Effect of Mixture Percentage

The effect of mixture percentage on pore pressure generation for gravel-sand mixtures was compared for specimens with 100% Ottawa C109 sand, 80% sand/20% Pea Gravel, 60% sand/40% Pea Gravel, 40% sand/60% Pea Gravel, and 100% Pea Gravel. Specimens were tested at σ_{v0}' = 100 kPa for D_r = 47% and D_r = 87% as shown in Figure 5. In Figure 5a, the data shows that mixture percentage does not have a significant effect on pore pressure generation for D_r = 47% specimens, with only a small increase observed for the 80% sand test. As discussed previously, the r_u at N/N_L = 1 for the Pea Gravel specimens was between 0.80-0.85, while for Ottawa C109 sand at N/N_L = 1, it was close to 1. For the gravel-sand mixtures, the r_u values were 0.85-0.90 at N/N_L = 1.

In Figure 5b, the data shows that D_r has a significant effect on gravel-sand mixtures and that the gravel portion of the mixture is controlling the behavior. The pore pressure generation for the 80% sand, 60% sand, and 40% sand mixtures increases compared to the 100% gravel specimen. The 80% and 60% sand specimens have the highest pore pressure ratio values throughout the tests. The 40% sand specimen falls between these specimens and the 100% gravel specimen, while the 100% sand specimen is much lower than the gravel-sand mixtures and 100% gravel.

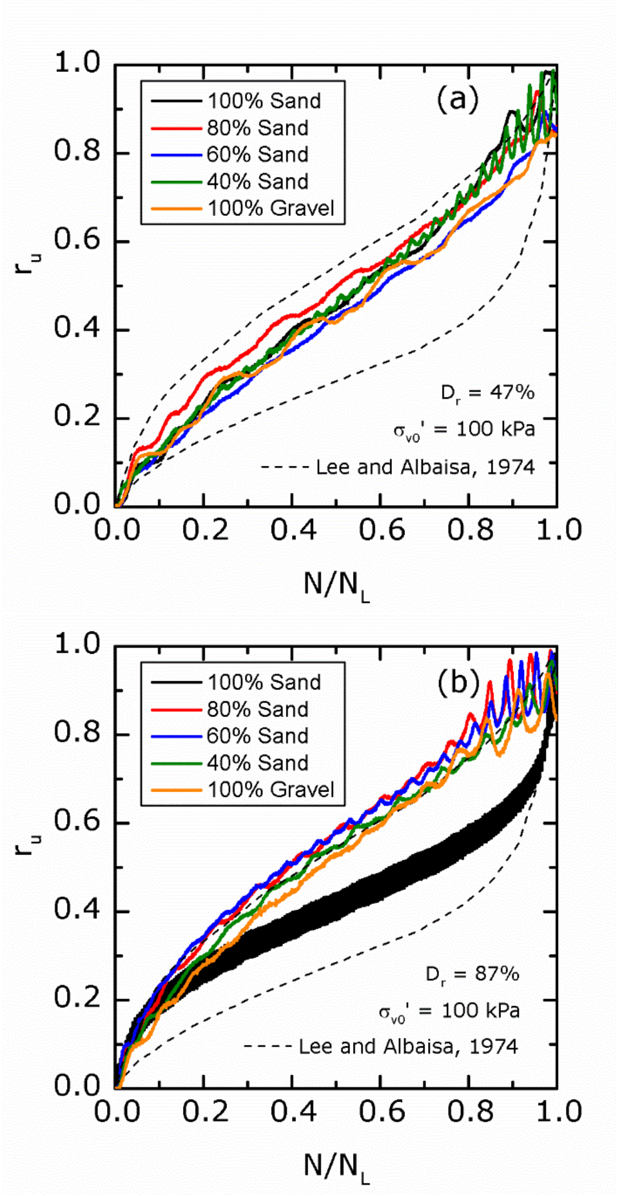

Figure 5. Effect of Mixture Percentage of Pea Gravel and Ottawa C109 Sand on Pore Pressure Generation for (a) D_r = 47% and (b) D_r = 87 %

3.4 Comparison to Literature

Data for existing upper and lower bound curves for pore pressure generation is shown in Figure 6 for comparison with data from this study for gravel and gravel-sand mixtures. Lee and Albaisa (1974) conducted triaxial tests on Monterey and Sacramento River sand. Evans and Seed (1987) conducted large-size triaxial tests on Watsonville gravels that were sluiced with sand to prevent compliance from membrane penetration. Haeri and Shakeri (2010) performed triaxial tests on Tehran alluvium that consists of sand and gravel. Banerjee et al. (1979) conducted triaxial tests on Oroville gravel, and Hynes (1988) conducted triaxial tests on Folsom gravel.

The data from this study falls close to the Evans and Seed (1987) data. The lower bound from this study is approximately the mid-range of Lee and Albaisa (1974), while the upper bound from this study falls above the upper bound of Lee and Albaisa (1974). The derived α values in Equation 1 (Seed et al., 1975) for the gravel and gravel-sand mixtures were 0.7 for the lower bound and 1.4 for the upper bound. Polito et al. (2008) observed similar behavior for sand and silt mixtures, with data falling in the middle to upper region of the Lee and Albaisa (1974) range. The Haeri and Shakeri (2010) and Banerjee et al. (1979) data have upper bounds that are significantly higher than the gravel and gravel-sand mixtures tested in this study. The lower bound from Haeri and Shakeri (2010) falls near the upper bound from this study. The Hynes (1988) data falls near or above the upper bound from this study. Combining this data shows that gravel and gravelly soil mixtures can have a wide range of pore pressure generation response. These differences may be explained by the gradation characteristics of the materials. The coefficient of uniformity ($C_u = D_{60}/D_{10}$) for the Oroville gravel tested by Banerjee et al. (1979) was 47, while the C_u of the Tehran alluvium tested in Haeri and Shakeri (2010) was 28. The gravels tested by Hynes (1988) and Evans and Seed (1987) had C_u values of 13 and 1.3, respectively. The C_u value for the Pea Gravel in this study was 1.6. When comparing these values to the pore pressure response in Figure 6, the effect of gradation can be observed. As gravelly soils become more well-graded their pore pressure generation increases rapidly in the first few cycles of loading and then flattens after reaching relatively high values of r_u in those first few cycles. The gravel in this study matches the gravel tested in Evans and Seed (1987) because they are both poorly-graded with C_u values less than 2. Hynes (1988) data falls in the middle because of its intermediate value of C_u compared to the other gravelly soils in Figure 6.

4 CONCLUSIONS

This study evaluated the pore pressure generation and some of the parameters that affect this response for Pea Gravel, Ottawa C109 sand, and gravel-sand mixtures. Specifically, the effect of initial vertical effective stress, relative density, and mixture percentage of gravel and sand was studied. For both Pea Gravel and Ottawa C109 sand, initial vertical effective stress was shown to have no effect on the pore pressure generation ratio.

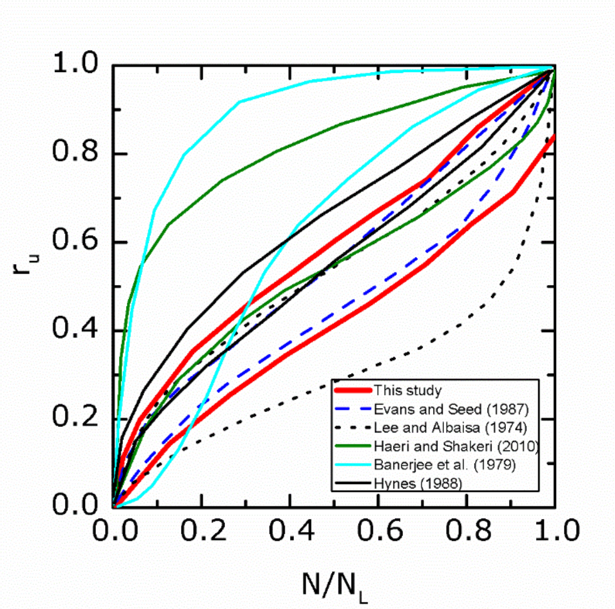

Figure 6. Comparison of Pore Pressure Generation with previous studies

It was observed that the r_u value at liquefaction (defined as 3.75% single amplitude shear strain) was only 0.80-0.85 for Pea Gravel while it was close to 1 for Ottawa C109 sand. An increase in relative density was shown to increase pore pressure generation for Pea Gravel.

The effect of mixture percentage on pore pressure generation was studied by preparing mixtures of Pea Gravel and Ottawa C109 sand with 80% sand/20% gravel, 60% sand/40% gravel, and 40% sand/60% gravel. For looser specimens at $D_r = 47\%$, mixture percentage did not have a significant effect on pore pressure generation, and data fell between the middle and upper region of the Lee and Albaisa (1974) data. For denser specimens at $D_r = 87\%$, the mixture percentage had a significant effect on pore pressure generation. For these gravel-sand mixtures, the gravel portion of the mixture controlled pore pressure generation response. The mixtures of 80% sand and 60% sand had the greatest pore pressure generation followed by 40% sand, 100% gravel, and 100% sand.

Results from this study for gravel and gravel-sand mixtures were compared to existing data on pore pressure generation from Lee and Albaisa (1974) for sands and Evans and Seed (1987), Haeri and Shakeri (2010), Banerjee et al. (1979), and Hynes (1988) for gravelly soils. The data from this study falls in a similar range to the Evans and Seed (1987) data. The lower bound from this study is approximately the mid-range of Lee and Albaisa (1974), while the upper bound from this study falls above the upper bound of the Lee and Albaisa (1974) range. The gradation characteristics of the gravel was shown to have a significant effect on pore pressure generation, with well-graded gravelly soils showing increased pore pressure generation in the first few cycles of testing compared to poorly-graded gravels. Therefore, C_u is shown to have a significant effect on pore pressure generation of gravelly soils, with r_u increasing with increasing C_u, especially at N/N_L less than 0.50.

5 ACKNOWLEDGMENTS

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