



Evaluating the Liquefaction Potential of Silty Sands in a Centrifuge

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ABSTRACT

A series of centrifuge tests was conducted on saturated models of fine Nevada sand with different silt contents to study the influence of non-plastic silt on the liquefaction potential of silty sands. Parameters such as acceleration and pore pressure were monitored throughout the tests. Relationship between cyclic stress ratio (CSR) versus silt content was introduced at different effective confining pressures considering the effect of intergranular, interfine and global void ratios. Results indicated that increasing silt content to a certain threshold value decreases the liquefaction resistance of soils.

RÉSUMÉ

Des essais en centrifugeuse ont été effectués sur des maquettes saturées de sable fin du Nevada, en variant le contenu de limon pour étudier l'influence du limon non-plastique sur le potentiel de liquéfaction des sables limoneux. Des paramètres tels que l'accélération et la pression des pores ont été contrôlés tout au long des essais. La relation entre les rapports de sollicitation cyclique et la proportion de limon a été présentée pour différentes valeurs de pression de confinement efficace de façon à tenir compte des variations de vides intergranulaires, entre les particules fines ainsi que le taux de vide global. Les résultats obtenus indiquent qu'une augmentation de la proportion de limon, jusqu'à l'atteinte d'une valeur de seuil, réduit la résistance du sol à la liquéfaction.

1 INTRODUCTION

The Northridge earthquake in Los Angeles, 1994, which generated extensive damage to buildings, roadways, bridges, and other civil engineering structures, with evidence of liquefaction occurring in several locations of fairly uniform sand that contains up to 28% of fines (<0.075 mm), shows the great demand for evaluating the liquefaction potentials of silty-sands. During The Imperial Valley earthquake of 1979, liquefaction occurred in silts with as little as 7 percent sand (Holzer et al. 1989). Liquefaction occurred in numerous tailings dams with silt content of 25% to 95% during the 1965 Chilean M7 earthquake (Dobry and Alvarez 1967). Many researchers have studied extensively the liquefaction behavior of clean sands but not enough studies have been performed for silts and sands with non-plastic fines. Recently, some studies focused on finding a definite criterion for evaluating the liquefaction potential of sands with non-plastic mixtures. Many case histories showed that sands containing non-plastic fines could also liquefy (Seed and Lee, 1966; Kuribayashi and Tatsuoka 1975; Seed et al., 1983; Zeghal and Elgamal 1994). Ishihara and Koseki (1989) indicated that there is no clear correlation between fines content and cyclic strength. Many studies have indicated conflicting results that the existence of non-plastic fines in sand mixture decrease their resistance to liquefaction (Troncoso and Verdugo 1985; Finn et al. 1994; Vaid 1994), or may increase their resistance to liquefaction (Chang et al. 1982; Dezfulian 1982; Seed et al. 1985). However, other studies showed that the liquefaction resistance of sands containing non-plastic fines initially decreases as fine content increases until some minimum resistance is reached, and then

increases as fine content increases (Law and Ling 1992; Koester 1994). Recently, some studies (Guo T. and Parakash S. 1999; Amini F. and Qi G. Z. 2000; Thavanayagam S. et al. 2000) focused on finding a definite criterion for evaluating the liquefaction potential of sands with non-plastic mixtures. The purpose of this study is to examine the influence of non-plastic silt content, voids ratio and effective confining pressure on the liquefaction potential of silty sands.

2 EXPERIMENTAL CONFIGURATION

A series of dynamic centrifuge tests was conducted at a scale of 50g on scaled pore fluid-saturated models of fine Nevada sand with different silt contents to study the influence of non-plastic silt content on the liquefaction potential of silty sands. A total of 10 cyclic liquefaction tests prepared in a laminar box were conducted at a scale of 50g and subjected to lateral base shaking with a prototype peak acceleration of 0.1 g comprising 40 cycles at 2 Hz prototype scale. These cyclic liquefaction tests were conducted on saturated models of fine Nevada sand (G_s of clean sand (SP group) = 2.66, and G_s of fines (ML group) = 2.63) considering two nominal void ratios of 0.62 and 0.7 and with silt contents of 0, 10, 20, 30 and 40%, Tables 1 and 2. The grain size distribution of clean Nevada sand is shown in Figure 1. In this series the number of cycles required for liquefaction as well as the cyclic resistance up to liquefaction were determined.

The non-plastic silt content, voids ratio and the initial effective vertical stress σ'_v are considered as major factors to affect liquefaction of granular soils. In this study, only void ratio is used as an index since there is

no ASTM procedure for determining relative density of soils with fine content more than 15%.

The silty sand specimens were prepared by the dry pluviation method that shown to create a grain structure that duplicates closely the anisotropy observed in naturally alleviated marine-deposited sands (Miura and Toki 1984, Lade and Yamamuro et al. 1997) as well as dry pluviation provides very low depositional energy into the specimen which is necessary to imitate alluvial deposits in creating a loose compressible specimen (Yamamuro et al. 1999). Ishihara, 1993 found that the steady state line was nearly the same for silty sand samples prepared at the same density by dry pluviation and water sedimentation methods.

The accelerometers and pore pressure transducers were placed at the proper orientations and locations during dry pluviation. The sample was de-aired by the application of vacuum to the prepared soil model and Carbon dioxide is used to displace the less soluble air that followed with the saturation process.

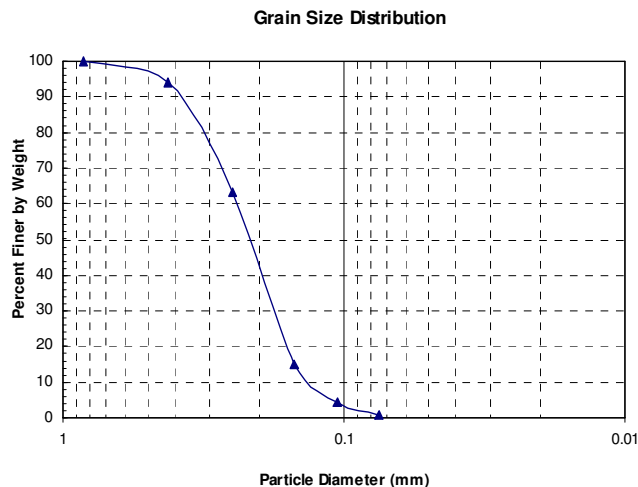


Figure 1. Grain-Size Distribution of Nevada Sand

3 TEST RESULTS AND ANALYSIS

The characteristic behaviour of saturated Nevada sand with different silt mixes during a cyclic base excitation was evident in all experiments. A total of 10 liquefaction tests were conducted at 50 g to determine the prototype behaviour in a centrifuge model, Table 2. Parameters such as acceleration and pore pressure are monitored and recorded throughout the tests. A sketch of the laminar box and instrumentations used for the soil model is presented in Figure 2.

The time histories of the recorded horizontal accelerations at prototype scale in the soil for two example tests of clean sand (test #1) and with slit content of 30% (test #7), Table 2, are given in Figure 3. Results show that the clean Nevada sand started to display a reduction in stiffness after approximately 10 seconds from the start of shaking (after about 21 cycles) however the Nevada sand with slit content of 30% showed an

immediate severe reduction in stiffness after about 5-2 seconds from base to top layers. The loss of shear strength for Nevada sand with slit content of 30% is observed after 6, 3, and 3 cycles at the depths of 4.3, 1.4 and 0.2 m, respectively.

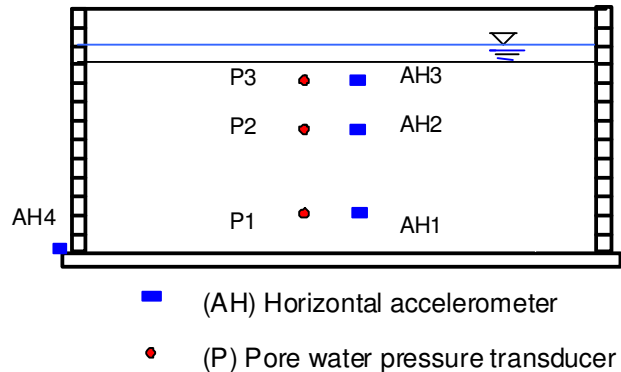


Figure 2. Schematic section of the centrifuge model and instrumentation

Figure 4 shows the relationships between excess pore pressure ratio at different depths, ($r_u = p / \sigma'_o$, where p is excess pore pressure and σ'_o is the initial effective vertical stress or the initial effective stress under triaxial condition) and the cycle ratio N/NL , (where N is the number of cycles and NL is the accumulative number of cycles causing liquefaction) for Nevada sand silt mixes compared with generation function proposed by Seed et al. (1976) with an average value of $\alpha=0.7$. Groups at different voids ratio and fines content are bounded in fairly narrow bands as shown in Figure 4. In general the records show a rapid build up of the pore pressure ratio during the first few cycles, and then increases at a decreasing rate as it near $r_u = 1$ while at this stage, the soil structure loses its integrity indicating initial liquefaction. The pore pressure buildup in silty sands at $FC < FC_{th}$ is much faster than in clean sand as demonstrated in Figure 4 (FC = fine grains content and FC_{th} = threshold fine grains content). The less permeable soil mixes at less voids ratio showed faster initial pore pressure buildup than that of higher voids ratio, Figure 4. Sand-silt mixes at less voids ratio showed closer trend with the proposed pore pressure pattern by Seed et al. (1976).

4 THE CORRELATION OF CONTACT INDICES WITH EXPERIMENTAL RESULTS

Global, intergranular and interfine void ratios are selected as constant parameters for all test series, Figure 5. Thevanayagam (2000) and Thevanayagam et al. (2002) proposed the equivalent intergranular void ratio $(e_c)_{eq}$ that considers the secondary influence of fines contributing to the active intergrain contacts and this relationship is represented by the factor b and $(e_c)_{eq}$ is considered as a

modification of intergranular void ratio e_c (Mitchell 1993 and Vaid 1994) into a contact density index at $FC < FC_{th}$:

$$(e_c)_{eq} = \frac{e + (1-b)f_c}{1 - (1-b)f_c}; \quad 0 < b < 1$$

[1]

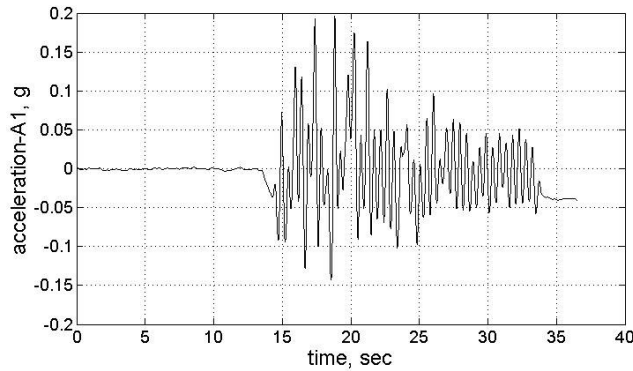


Figure 3-a. Acceleration histories for clean Nevada sand at depth = 4.3 m, $e \sim 0.7$

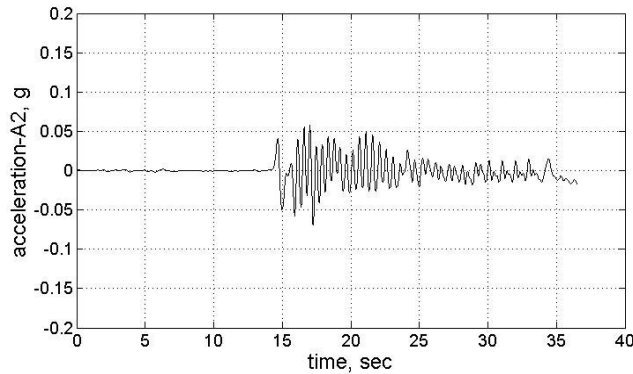


Figure 3-b. Acceleration histories for clean Nevada sand at depth = 1.4 m, $e \sim 0.7$

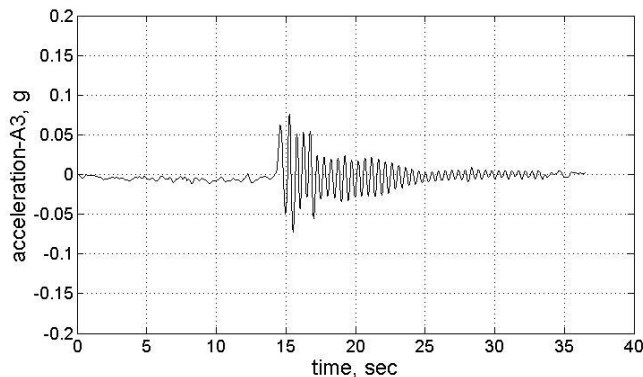


Figure 3-c. Acceleration histories for clean Nevada sand at depth = 0.2 m, $e \sim 0.7$

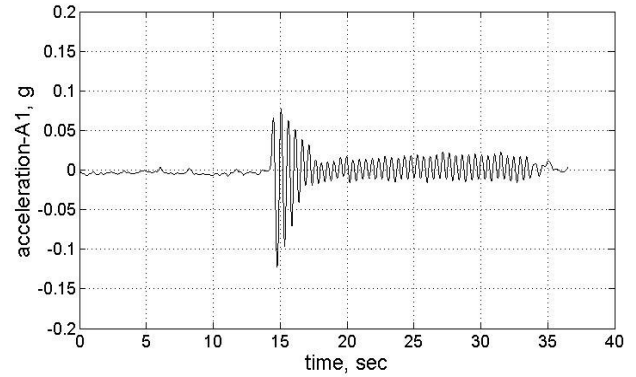


Figure 3-d. Acceleration histories for Nevada sand silt mix at depth = 4.3 m, $e \sim 0.7$, $FC = 30\%$

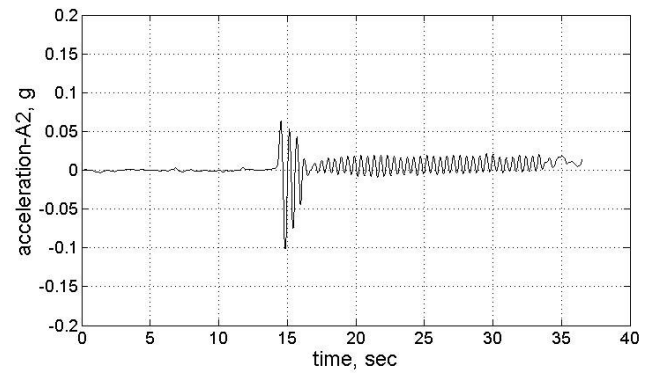


Figure 3-e. Acceleration histories for Nevada sand silt mix at depth = 1.4 m, $e \sim 0.7$, $FC = 30\%$

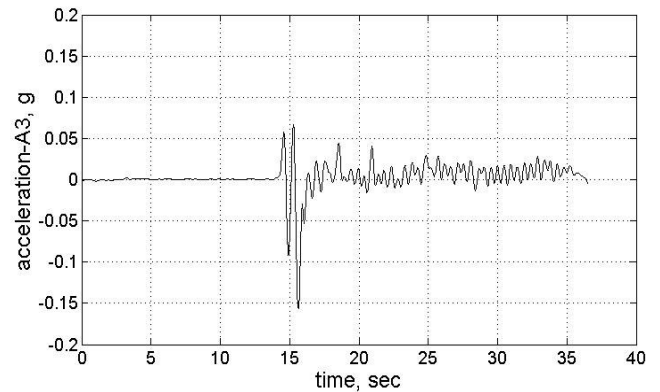


Figure 3-f. Acceleration histories for Nevada sand silt mix at depth = 0.2 m, $e \sim 0.7$, $FC = 30\%$

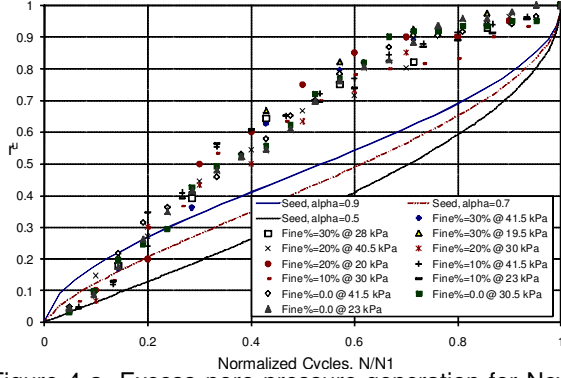


Figure 4-a: Excess pore pressure generation for Nevada sand silt mixes at $e \sim 0.7$, $FC < FC_{th}$

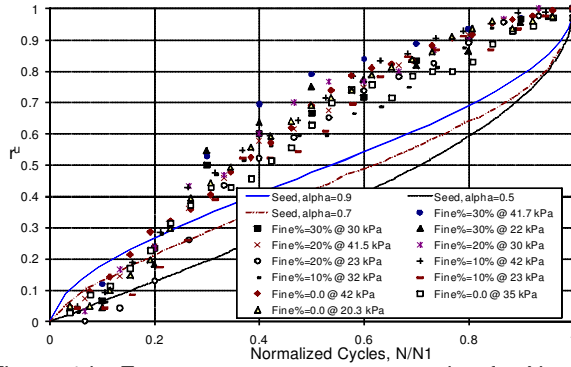


Figure 4-b: Excess pore pressure generation for Nevada sand silt mixes at $e \sim 0.62$, $FC < FC_{th}$

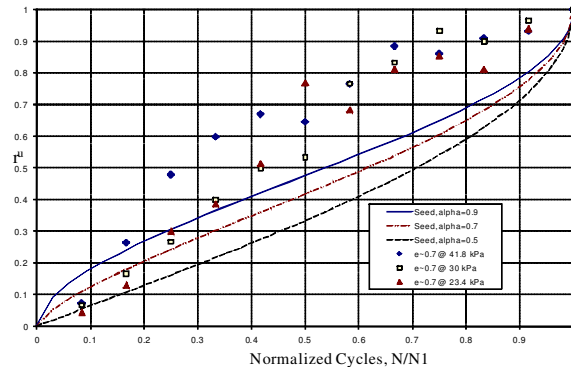


Figure 4-c: Excess pore pressure generation for Nevada sand silt mix at $e \sim 0.7$, $FC = 40\%$

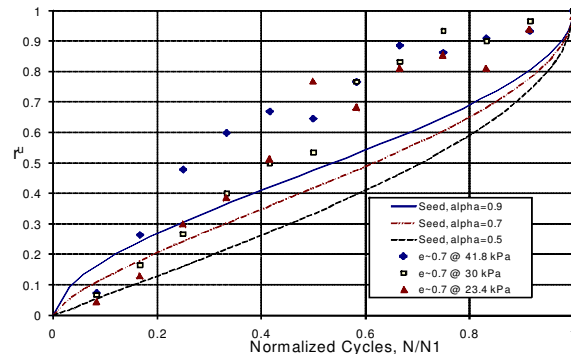


Figure 4-d: Excess pore pressure generation for Nevada sand silt mix at $e \sim 0.62$, $FC = 40\%$

$$e_c = \frac{e + f_c}{1 - f_c} \quad [2]$$

Where $f_c = FC/100$; FC = fine grains content; FC_{th} = threshold fine grains content; b = portion of the fine grains that contribute to the active intergrain contacts; and e = global void ratio, Thevanayagam (2000). The $(e_c)_{eq}$ values for the two tested sand series are listed in Tables 2 and 3. Figure 6-a and b shows that there is no unique relationship between the global void ratio and both the numbers of cycles required for liquefaction and the cyclic stress ratio of Nevada sand silt mix results, however, $(e_c)_{eq}$ showed a consistent relationship with these data at factor $b = 0.7$ as shown in Figure 6-c and d at three stress levels for tests 1 to 8 with $FC < FC_{th}$, Table 2. In this test series only two tests were conducted with $FC > FC_{th}$ which made it difficult to obtain parameter m required for the equivalent interfine void ratio $(e_f)_{eq}$ at $FC > FC_{th}$ which defined by Thevanayagam et al. (2002):

$$(e_f)_{eq} = \frac{e}{f_c + \frac{1 - f_c}{(R_d)^m}} \quad [3]$$

Although the condition of coarser grain size to be at least 6.5 times larger than the finer grain size (Thevanayagam et al. 2000) is fulfilled for Nevada sand-silt mix ($R_d = D_{50}/d_{50} = 7.76$, Table 1) to satisfy case I, Figure 5, so that finer grains just act as fillers and not active in the transfer of interparticles forces (Thevanayagam et al. 2000), it was not possible to prepare the soil mix such that finer grains are fully confined and freely move within the void spaces between the coarser-grains. The microstructure of these soil mixes showed an increase in both intergranular void ratio ($e_c > e_{max,HC}$) and interfine void ratio ($e_f > e_{max,HF}$) for Nevada sand-silt mix at FC 10%-30% while it was predictable that finer grains would actively contribute to the stress-strain response and match case III (Figure 5) at $0.0 < FC < FC_{th}$. The data for these sand-fines mixes fall in the vicinity of the data of the respective host clean sands (Thevanayagam et al. 2002) while some fines act in load transfer between some coarse grain particles and the remainder act as filler of voids (Thevanayagam et al. 2000) with limited threshold values of $FC_{th} = 30\%$ for Nevada sand. Nevada sand-silt mixes with $e \sim 0.7$ (test # 3, 5 and 7, Table 2) show an increase in the intergranular void ratio to indicate the existence of partial layering and partial separation of coarser grains of Nevada sand by the finer silt grains (case III) however for $e \sim 0.62$ (test # 4, 6 and 8, Table 2) still does not exclude the intergranular matrix from partial layering and partial separation (case III), Figure 5. The expected FC_{th} values corresponding to $e = 0.7$ and 0.62 based on equation (3) (Thevanayagam et al. 2000) are ≤ 35 and 28% , respectively. Hence there were no enough data at high FC , the limit fines content, FC_L , predictions for Nevada silt mixes were not available.

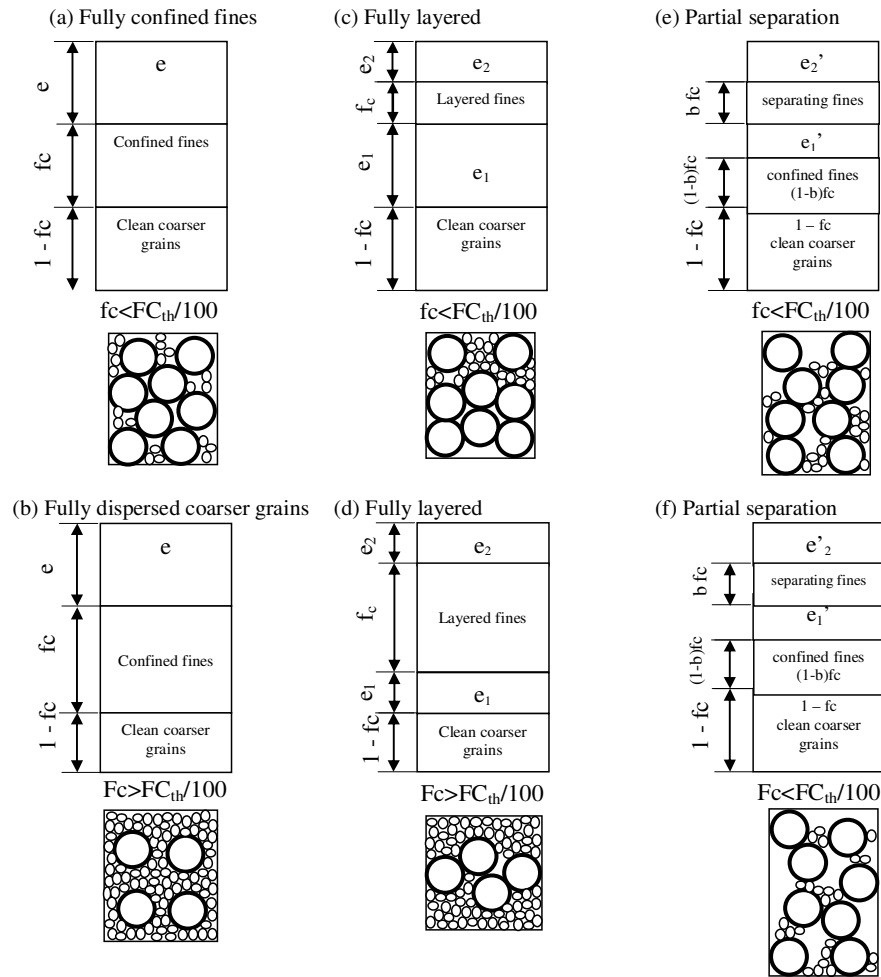


Figure 5. Phase diagram of microstructure and intergranular soil mix classification (after Thevanayagam 2000)

Table 1. Index properties for tested sand mixes

Sand	FC%	D ₅₀ (mm)	d ₅₀ (mm)	e _{max,HC}	e _{max,Hf}	C _{uc}	C _{uf}	R _d	χ	b
Nevada	0 to 40	0.22	0.028	0.752	1.595	1.898	8.75	7.76	4.55	0.7

Table 2. Properties and microstructure classifications of Nevada sand slit mixes

Test #	% Fine	e	(e _c) _{eq}	e _f	e _f >e _{max,HF}	e _c	e _c >e _{max,HC}	Case	(e _c) _{eq}	(e _f) _{eq}
1	0	0.69	0.69	0	--	0.69	No	--	--	--
2	0	0.62	0.62	0	--	0.62	No	--	--	--
3	10	0.70	0.75	7.0	Yes	0.89	Yes	III	Yes	No
4	10	0.63	0.68	6.27	Yes	0.81	Yes	III	Yes	No
5	20	0.70	0.81	3.49	Yes	1.12	Yes	III	Yes	No
6	20	0.62	0.73	3.11	Yes	1.03	Yes	III	Yes	No
7	30	0.70	0.87	2.34	Yes	1.43	Yes	III	Yes	No
8	30	0.69	0.85	2.28	Yes	1.41	Yes	III	Yes	No
9	40	0.62	0.85	1.56	No	1.71	Yes	IV-2	No	Yes
10	40	0.59	0.81	1.48	No	1.65	Yes	IV-2	No	Yes

e_{max,HC}=0.75, e_{max,HF}=1.595, e: global void ratio, e_c: intergranular void ratio, e_f: interfine void ratio

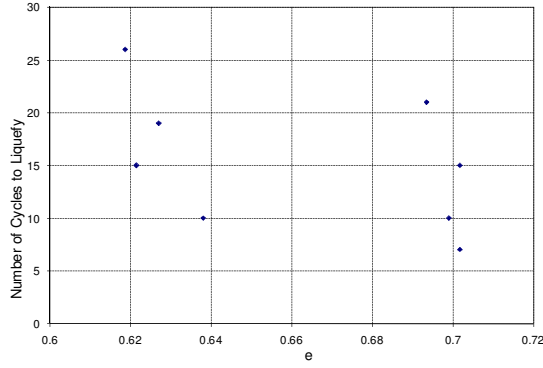


Figure 6-a: Nevada sand at different silt content with e

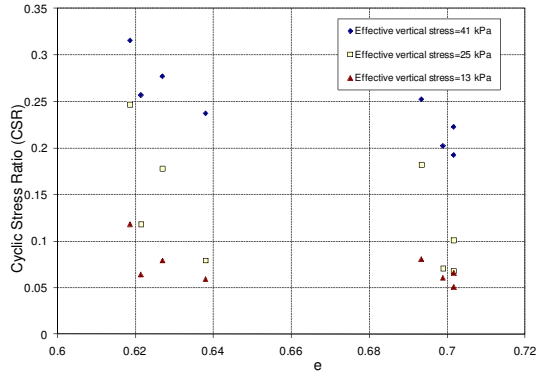
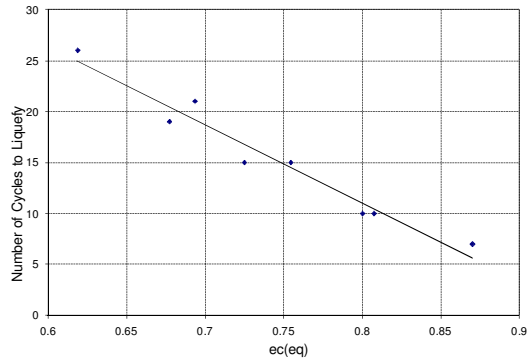
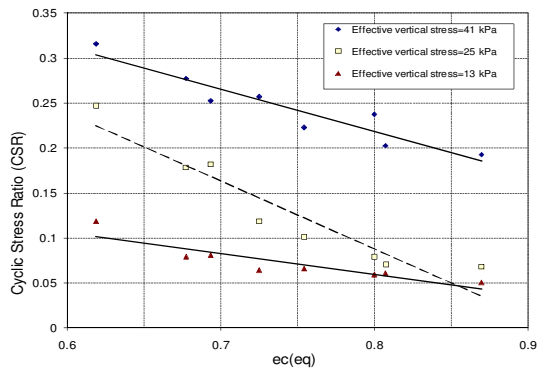


Figure 6-b: Nevada sand at different silt content with e

Figure 6-c: Nevada sand at different silt content with $(e_c)_{eq}$ with $b=0.7$ Figure 6-d: Nevada sand at different silt content with $(e_c)_{eq}$ with $b=0.7$

$$FC_{th} \leq \frac{100e_c}{1 + e_c + e_{max,Hf}} \% \quad [4]$$

Comparing Nevada test series of $e \sim 0.7$ with $e \sim 0.62$, the separation fines for $e \sim 0.7$ is more than for $e \sim 0.62$ resulting an increase of instability for the intergranular matrix for $e \sim 0.7$ therefore more susceptible for liquefaction than the second case and requiring less number of cycles to liquefaction compared with $e \sim 0.62$, Figure 7.

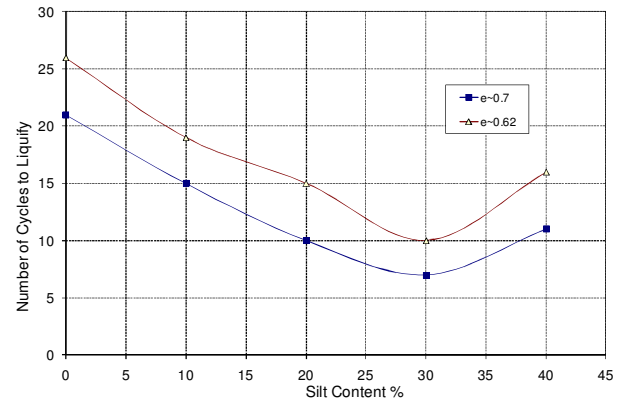


Figure 7: Number of cycles to liquefy at different silt content

5 CONCLUSIONS

A total of 10 cyclic liquefaction tests were conducted on saturated models of fine Nevada sand with different silt contents to study the influence of non-plastic silt content on the liquefaction potential of silty sands. In these tests the number of cycles required for liquefaction was determined. Test results show that cyclic strength decreases with increasing fines content to a certain threshold value then increases. Lowest cyclic strength occurred at 30 percent fines.

The pore pressure buildup in silty sands at $FC < FC_{th}$ is much faster than in clean sand while the less permeable soil mixes at less voids ratio showed faster initial pore pressure buildup than that of higher voids ratio. An immediate reduction of shear strength for Nevada sand with slit content of 30% is observed compared with clean sand.

Test results showed that there is no unique relationship between the global void ratio and both the numbers of cycles required for liquefaction and the cyclic stress ratio of Nevada sand silt mix results. However, $(e_c)_{eq}$ showed a consistent relationship with these data with $FC < FC_{th}$. The microstructure of the tested soil mixes showed an increase in both intergranular void ratio ($e_c > e_{max,HC}$) and interfine void ratio ($e_f > e_{max,HF}$) at FC 10%-

30% while it was predictable that finer grains would actively contribute to the stress-strain response and match case III at $0.0 < FC < FC_{th}$. Nevada sand-silt mixes with $e \sim 0.7$ show an increase in the intergranular void ratio to indicate the existence of partial layering and partial separation of coarser grains of Nevada sand by the finer silt grains (case III). However, for $e \sim 0.62$ it does not exclude the intergranular matrix from partial layering and partial separation (case III). Comparing Nevada test series of $e \sim 0.7$ with $e \sim 0.62$, the separation fines for $e \sim 0.7$ is more than for $e \sim 0.62$ resulting an increase of instability for the intergranular matrix for $e \sim 0.7$. Therefore, it is more susceptible for liquefaction than the second case and requiring less number of cycles to liquefaction compared with $e \sim 0.62$.

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