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THE EFFECT OF NON-PLASTIC FINES ON THE LIQUEFACTION RESISTANCE OF SANDS

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ABSTRACT

The paper presents results of a laboratory investigation into the effect of fines on the liquefaction resistance of sandy soils. The investigation was conducted by means of cyclic triaxial tests on a clean sand and its mixtures with a non-plastic silt at various contents and mean effective stress levels. The tests results for both the sand and the mixtures show that liquefaction resistance decreases with increasing mean effective stress at a given void ratio and also with increasing void ratio at a given constant mean effective stress. At a given void ratio and mean effective stress, liquefaction resistance decreases with increasing fines content up to a threshold value, beyond this value the liquefaction resistance starts to increase. The threshold fines content depends on the mean effective stress level and the characteristics of sand and silt. When intergranular void ratio is constant, liquefaction resistance increases with increasing fines content. The effect of fines on the liquefaction resistance in terms of intergranular void ratio is in agreement with the proposed in the semi-empirical procedures when evaluating liquefaction potential.

Keywords: liquefaction, non-plastic, fines, sands, void ratio

INTRODUCTION

Field observations from earthquake-induced failures due to liquefaction have shown, that for sandy soils, the amount of fines (%<75μm) they contain has a great influence on their liquefaction resistance. Seed et al. (1983), based on field performance data from liquefied and non-liquefied sites, proposed an empirical correlation between the cyclic stress ratio, $CSR=\tau_{av}/\sigma'_o$, and the corrected number of blow counts from Standard Penetration Test, $(N_1)_{60}$, for clean sands, as well as for silty sands with fines content greater than 5% and earthquake magnitude, M=7.5. According to this correlation, the presence of fines in silty sands increases their liquefaction resistance and consequently decreases the potential of liquefaction development. This beneficial effect of fines on the liquefaction resistance of silty sands has been adopted in all modern codes, (NCEER, 1997 and Eurocode 8), Figure 1.

In laboratory, although numerous studies have been performed in order to investigate the effect of fines content on the liquefaction resistance of silty sands, the results appear to be conflicting. Ishihara (1996) and Amini & Qi (2000), among others, found that the liquefaction resistance increases with increasing fines content (positive effect), others like Troncoso & Verdugo (1985), Vaid (1994) and Miura et al. (1995) suggested that the liquefaction resistance decreases with increasing fines content (negative effect), whereas others like Thevanayagam et al. (2000), Polito (2001), Xenaki & Athanaso-

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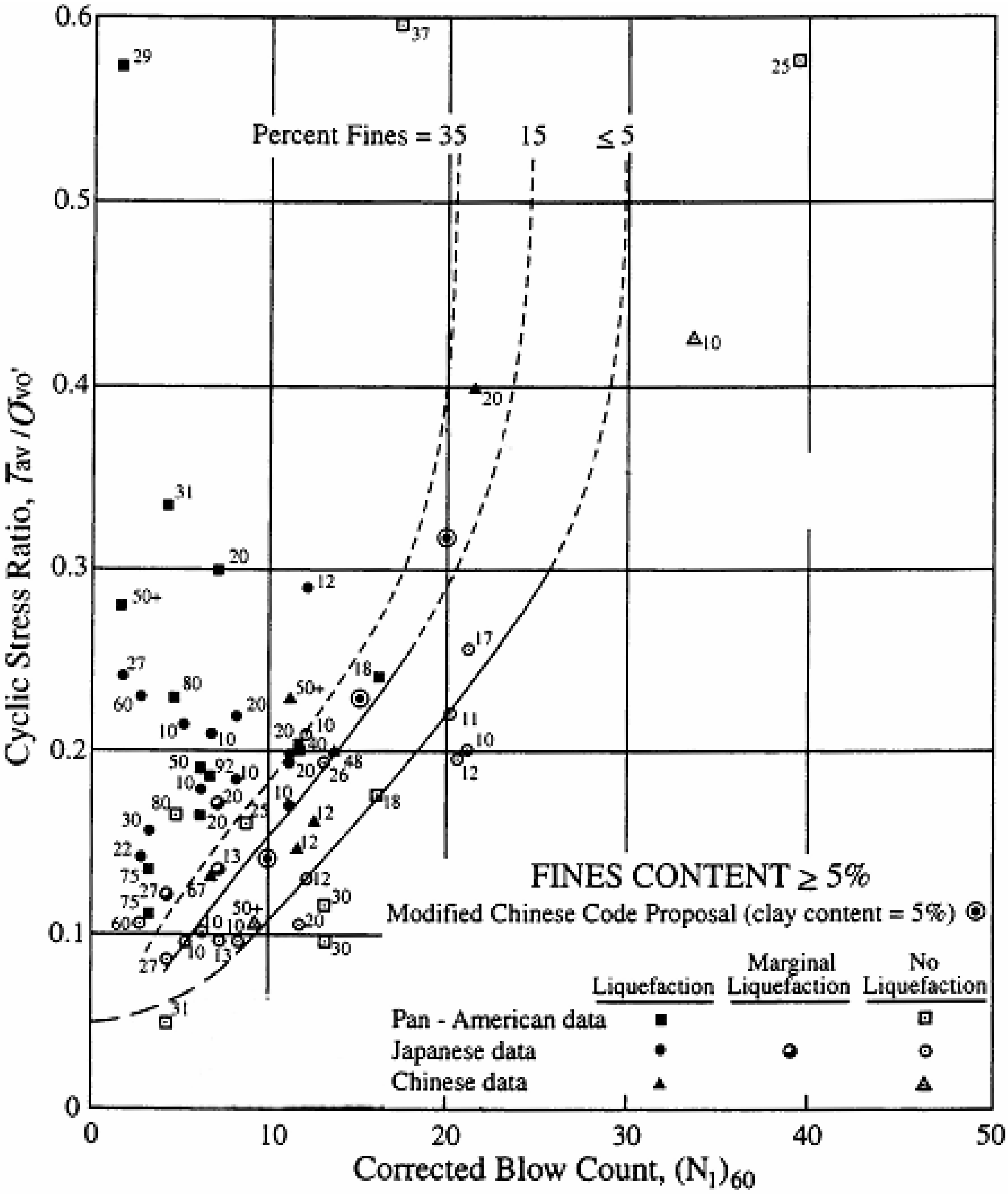


Figure 1. Relationship between cyclic stress ratio causing liquefaction, CSR=τ_{av}/σ'_o, and $(N_1)_{60}$ for silty sands and M=7.5 earthquake (NCEER, 1997)

poulos (2003) and Yang et al. (2004) found that there is an increase of liquefaction resistance with increasing fines content up to a certain value and a decrease thereafter with further increasing fines content. The fines content at which the effect of fines changes from positive to negative has been termed as threshold, or limiting, or transitional. Finally, Bouckovalas et al. (2003) suggested that mean effective stress is the main parameter determining the type of the effect of fines on the liquefaction resistance and used the critical state theory to support this (Been and Jefferies, 1985).

The purpose of the work presented in this paper is to clarify the effect of non-plastic fines on the liquefaction resistance of sands.

TESTED MATERIALS

The sand used in the testing programme was a clean quartz sand with well-rounded grains (D_{50}=0.30mm, C_u=1.3, G_s=2.64). The non-plastic silt was a ground product of natural quartz deposits (D_{50}=0.02, G_s=2.663 and C_u=7.5). Grain size distributions of both the sand and the silt are presented in Figure 2. Tests were carried out on the sand, the silt and their mixtures with silt content varying from 5 to 60%.

Although the ASTM (D 4243 & D 4254) test methods for the determination of minimum and maximum void ratios are applicable to soils that may contain up to 15%, by dry mass, of soil particles passing a No. 200 (75-µm) sieve, provided they have cohesionless characteristics, both these methods were used in this work in conjunction with others in order to get a consistent value. In particular, for the determination of the minimum void ratio both the vibratory table (ASTM D 4253, Method 2A) and the Standard Proctor test methods were used. The maximum void ratio was determined in accordance with the ASTM (D 4254, Method C) test method and also by pouring dry material in a mould three times and considering the average as the maximum value. Figure 3 shows the variation of the minimum and maximum void ratios with fines content.

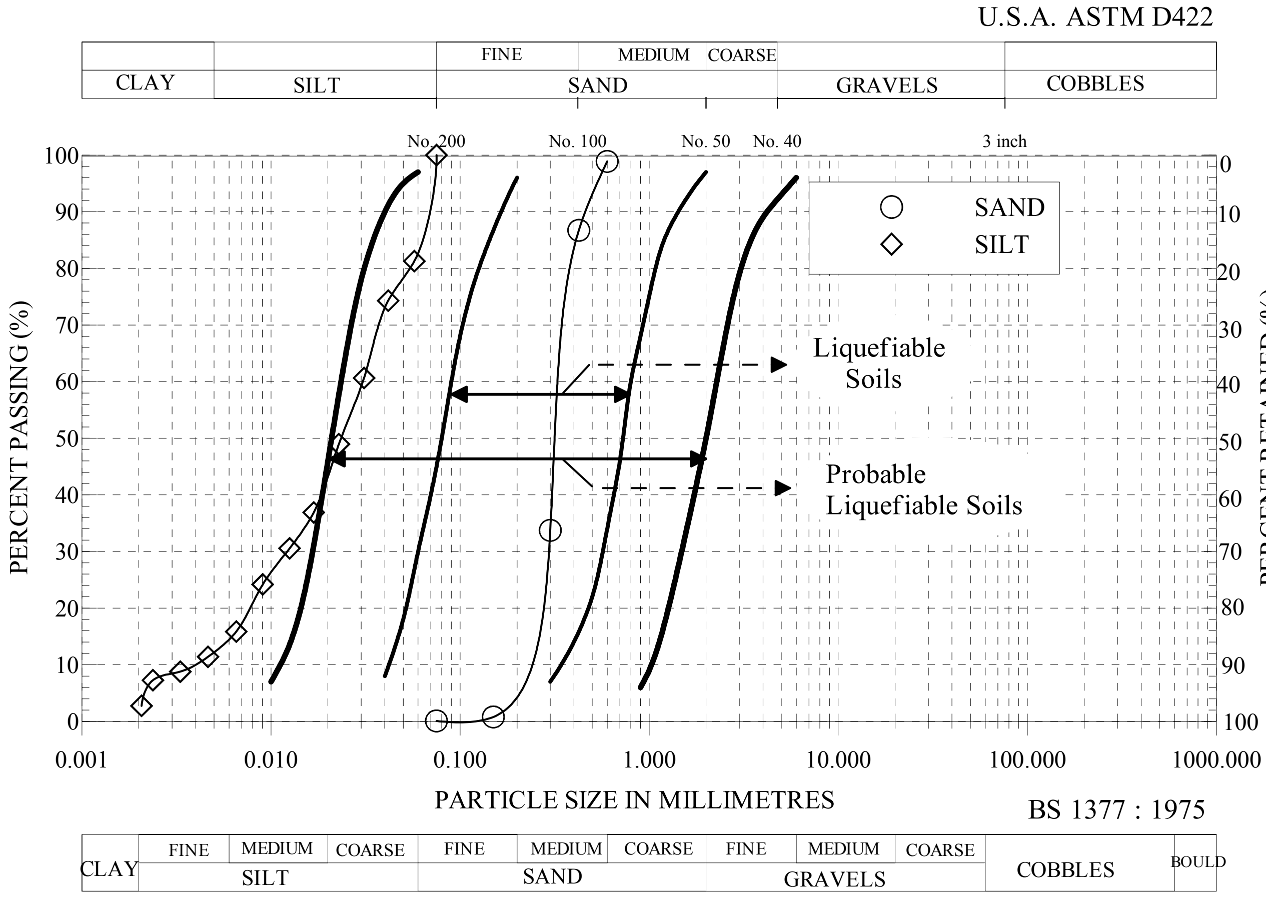


Figure 2. Grain size distributions of sand and silt

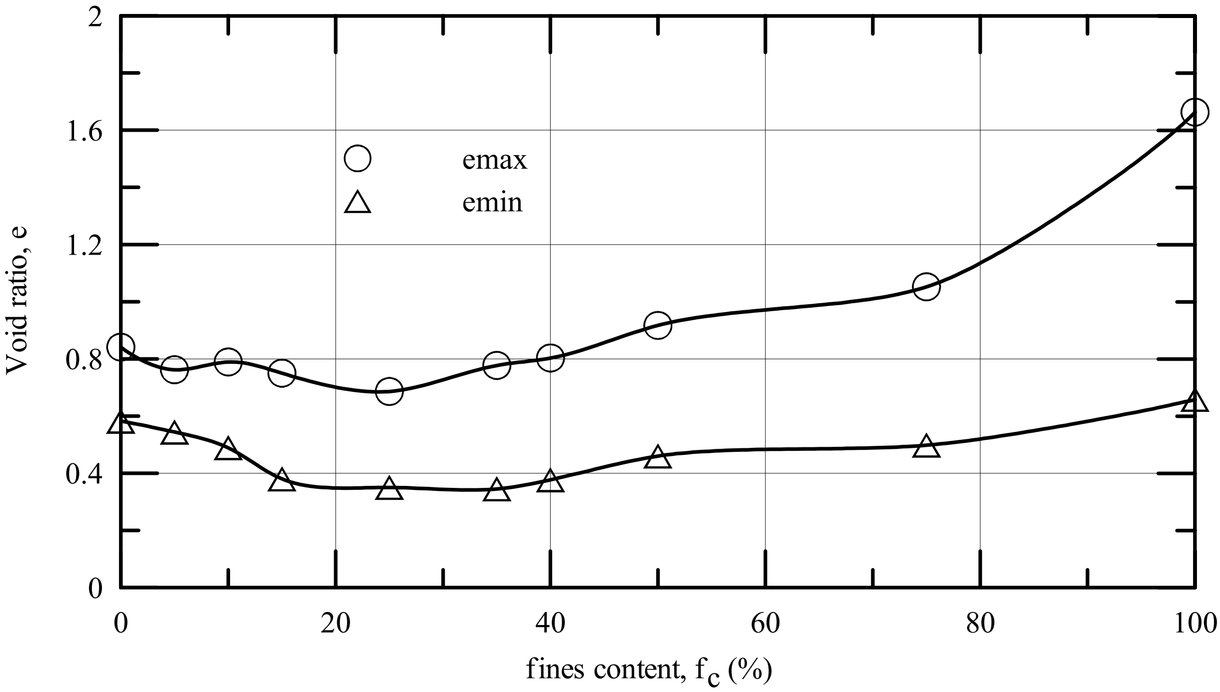


Figure 3. Variation of maximum, e_{max}, and minimum, e_{min}, void ratios with fines content, f_c

TESTING PROGRAMME

Testing was performed using the cyclic triaxial apparatus (MTS Systems Corporation, U.S.A). Its principles of operation are given in detail in Papadopoulou (2007).

The specimens (height/diameter≈100mm/50mm) were formed by moist tamping at a water content varying between 4% and 35%, using the undercompaction method, introduced by (Ladd, 1978). This sample preparation method was preferred, as it produces uniform specimens at various densities. Saturation was achieved by means of the carbon dioxide (CO_2) method. In all the tests the parameter of pore water pressure, $B=\Delta u/\Delta\sigma$, had values from 0.95 to 1.00. The specimens were then isotropically consolidated to the desired effective stress. Tests were conducted at various densities and effective stresses of 50, 100 and 300kPa.

During cyclic loading, the specimens were subjected to a sinusoidally varying axial stress ($\pm\sigma_d$) at a frequency of f=0.1 Hz under undrained conditions. In this work, cyclic stress ratio, $CSR=\sigma_d/2\sigma'_o$, corresponds to double amplitude axial strain, $\varepsilon_{DA}\approx5\%$ and liquefaction resistance or cyclic resistance ratio, CRR_{15}, is defined as the cyclic stress ratio, $CSR=\sigma_d/2\sigma'_o$, required to cause double amplitude axial strain, $\varepsilon_{DA}\approx5\%$ at 15 cycles of loading.

TEST RESULTS AND DISCUSSION

Several studies have considered sands containing fines as consisting of two matrices, the sand grains matrix and the fine matrix and analysed the interaction with each other (Vaid, 1994, Thevanayagam et al., 2000, Polito, 2001, Xenaki & Athanasopoulos, 2003 and Yang et al., 2004). At low fines content, the fines are mainly contained within the intergranular voids of sand grains and may not actively participate in transferring or sustaining any forces. However, with increasing fines content up to the threshold value, they not only fill the intergranular space, but they begin to displace the sand grains contacts. If the fines content exceeds the threshold value, the behaviour of the mixture is primarily governed by the contacts between the fines and the sand grains float within the fines matrix. The nature of the contribution of sand and fines matrices may be expressed in terms of their void ratio, the intergranular and interfine void ratio respectively.

The intergranular void ratio, e_g, expresses the relative contribution of sand fraction on the behaviour of mixture and is given by the following equation (Mitchell, 1975):

$$e_g = \frac{V_{FINES} + V_V}{V_{SAND}} = \frac{f_c + w^*\left(G_{SF} / S_r\right)}{\left(1 - f_c\right)^*\left(G_{SF} / G_{SG}\right)} \tag{1}$$

where V_{FINES} is the volume of the silt grains, V_V is the volume of the voids, V_{SAND} is the volume of the sand grains, f_c is the fines content, w is the water content of the specimen, G_{SF} is the specific gravity of the silt grains and G_{SG} is the specific gravity of the sand grains. For saturated specimens (S_r=100%) and considering that $G_{SF} \approx G_{SG}$, the intergranular void ratio after the consolidation of the specimen is expressed as follows:

$$e_g = \frac{f_c + e_c}{\left(1 - f_c\right)} \tag{2}$$

where e_c is the void ratio of the specimen after consolidation.

For mixtures with fines content exceeding the threshold, when the sand grains have little or no effect on their behaviour (V_{SAND} may be ignored), the interfine void ratio, e_f, may be a more appropriate parameter to be used (Thevanayagam & Mohan, 2000):

$$e_f = \frac{e_c}{f_c} \tag{3}$$

In the following the effect of the various parameters, such as mean effective stress, void ratio, fines content and intergranular void ratio or interfine void ratio on the cyclic stress ratio and liquefaction resistance of the tested materials is presented and then discussed.

The effect of mean effective stress on cyclic stress ratio at constant void ratio is shown in Figure 4. At a given number of cycles a decrease of cyclic stress ratio with increasing mean effective stress is observed both for the sand and the mixtures. This trend is in agreement with the empirical overburden correction factor, K_σ, used when evaluating the liquefaction resistance (Idriss & Boulanger, 2004).

The variation of liquefaction resistance with void ratio at constant mean effective stress is plotted in Figure 5. A decrease of liquefaction resistance with increasing void ratio is observed for each tested material.

Figure 6 shows the effect of fines content on cyclic stress ratio at constant void ratio and mean effective stress. At a given number of cycles, cyclic stress ratio first decreases with increasing fines content up to a threshold value and increases thereafter with further increasing fines content. The threshold fines content is about 35% and 30% at σ'_o=100 and 300 kPa respectively. These values are in agreement with the findings of previous studies (Polito & Martin, 2001, Xenaki & Athanasopoulos, 2003, Yang et al., 2004). The variation of liquefaction resistance with fines content at a constant void ratio is plotted in Figure 7 at σ'_o=100 and 300 kPa. There are indications that the threshold fines content depends not only on mean effective stress, but also on the characteristics of the sand and fines

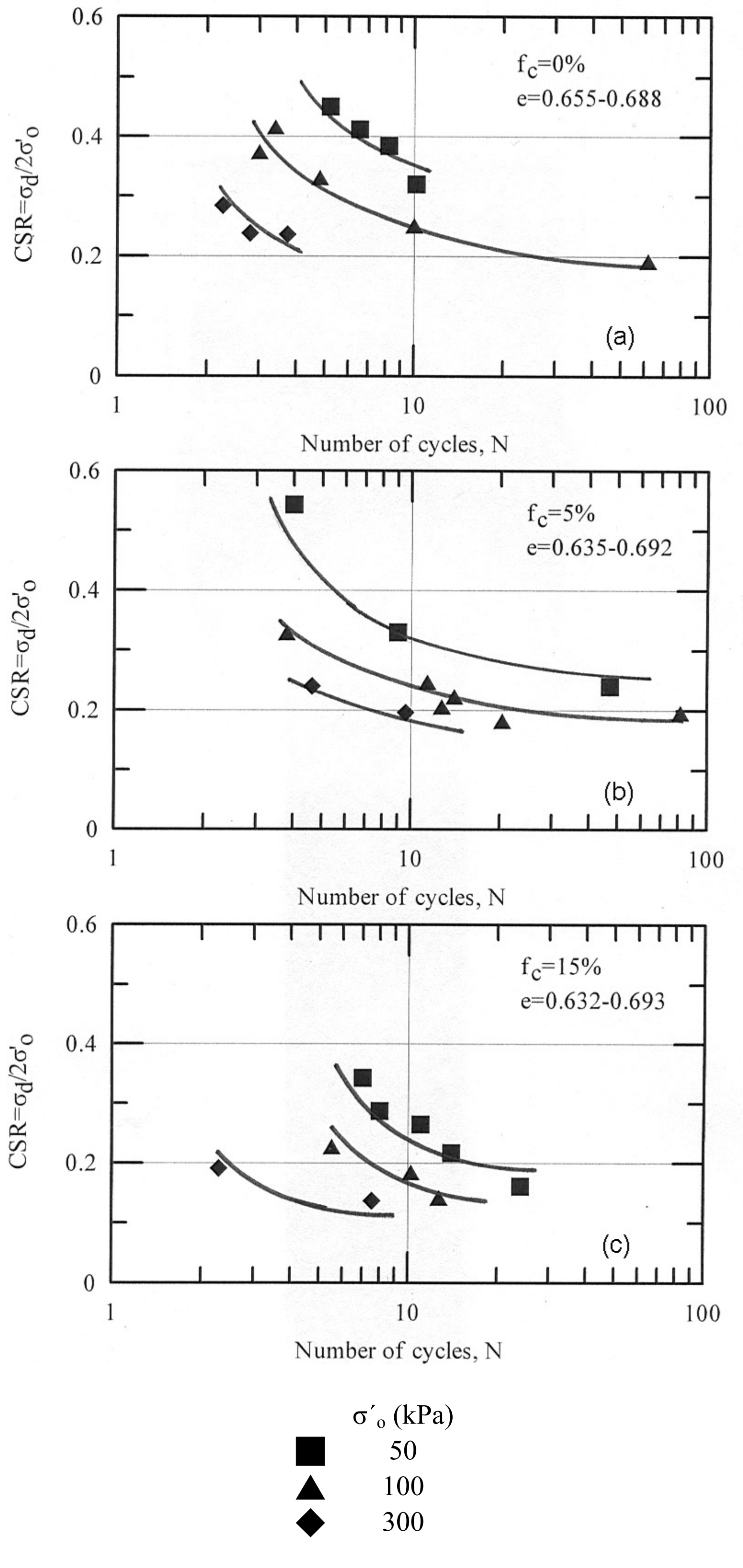


Figure 4. Variation of cyclic stress ratio, $\sigma_d/2\sigma'_o$, with number of cycles, N, at constant void ratio, e, and various levels of mean effective stress, σ'_o, for sand (a), f_c=5% (b) and f_c=15% (c)

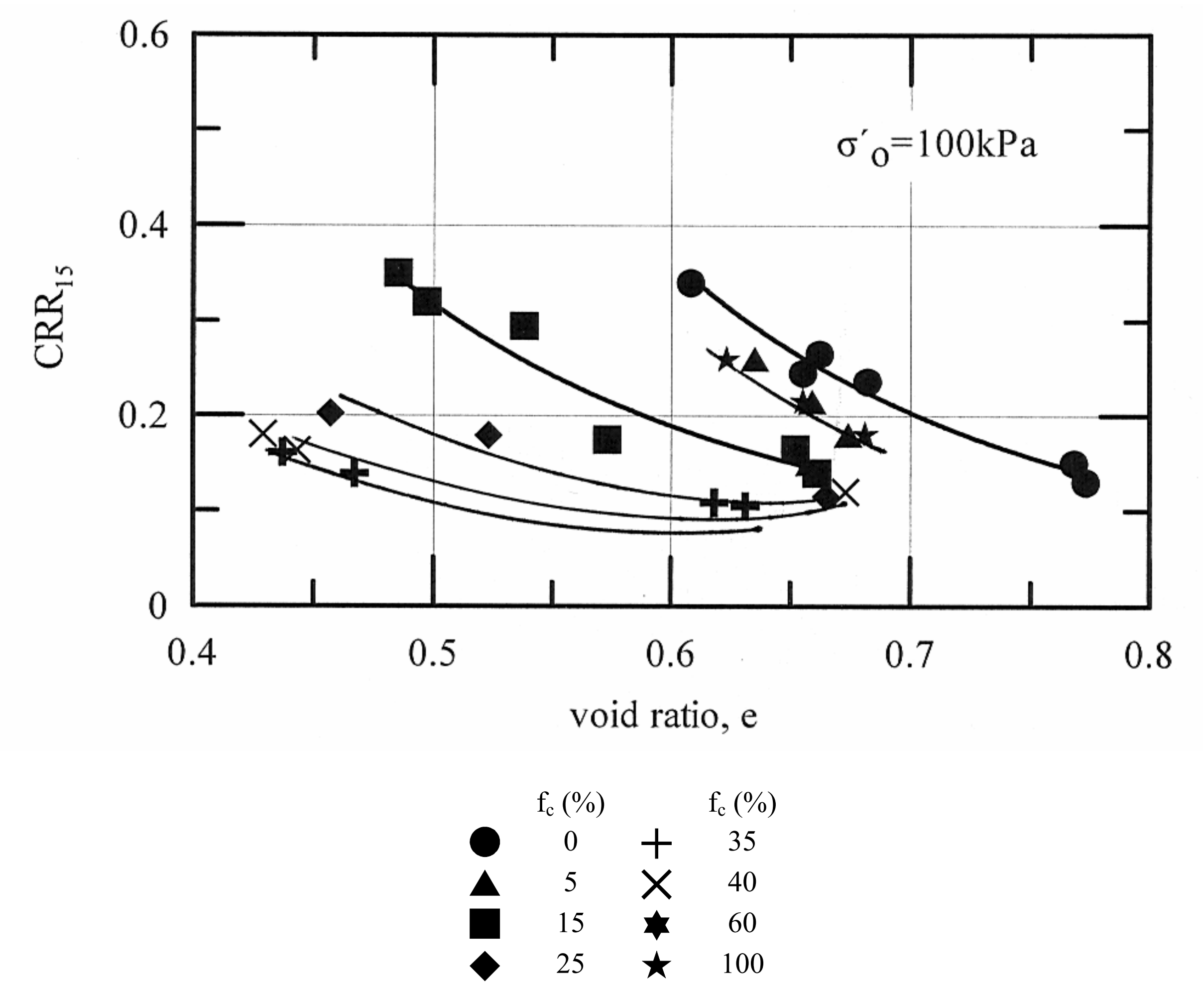


Figure 5. Variation of liquefaction resistance, CRR_{15} with void ratio, e, at various fines contents, f_c, and constant mean effective stress, σ'_o

and in particular the ratio of the mean particle diameter of the sand and the fines (Papadopoulou, 2007). The results in Figure 7 also show that once liquefaction resistance reaches a minimum at the threshold fines content, it remains thereafter relatively constant irrespectively of the fines content, unless the latter is increased significantly. The range of fines content at which liquefaction resistance is constant is broader at the mean effective stress of σ'_o=300kPa.

Figure 8 shows the variation of liquefaction resistance with intergranular or interfine void ratios at a constant mean effective stress. In accordance with the above stated, for the mixtures with fines content above the threshold value (f_c>40%), the interfine void ratio is used, as at high fines content the presence of sand grains has little or no effect on the force chain. For each material tested, it is shown that liquefaction resistance decreases with increasing intergranular or interfine void ratio. However at a given intergranular void ratio, liquefaction resistance increases with increasing fines content. This may be attributed to the fact that at constant intergranular void ratio, void ratio decreases with increasing fines content and thus the soil becomes stronger. This positive effect of fines on liquefaction resistance is in agreement with that suggested in the semi-empirical procedures for evaluating liquefaction potential during earthquakes. In particular, for the SPT-based procedure, this agreement may indicate that a constant N_{SPT} value corresponds to a constant intergranular void ratio value.

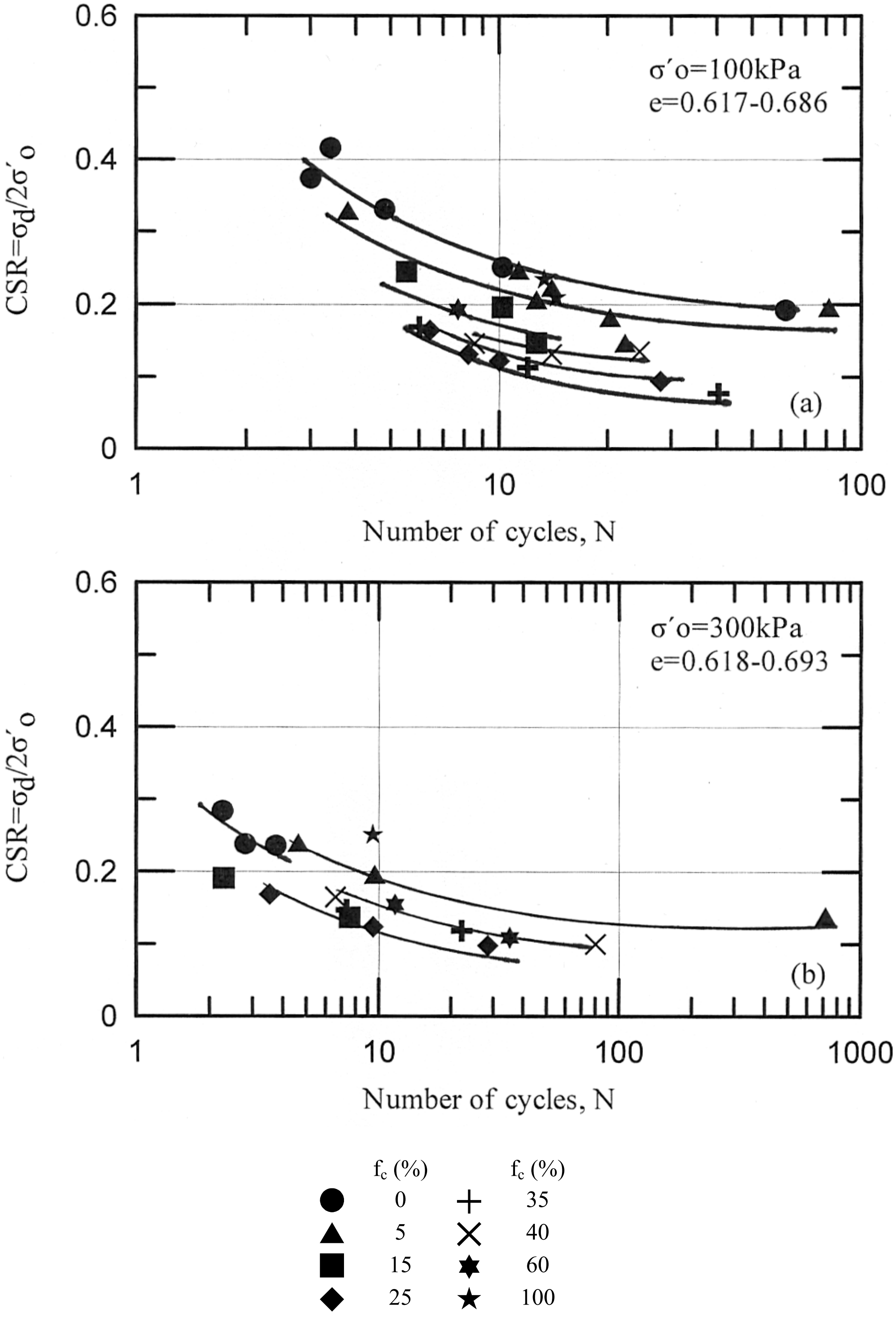
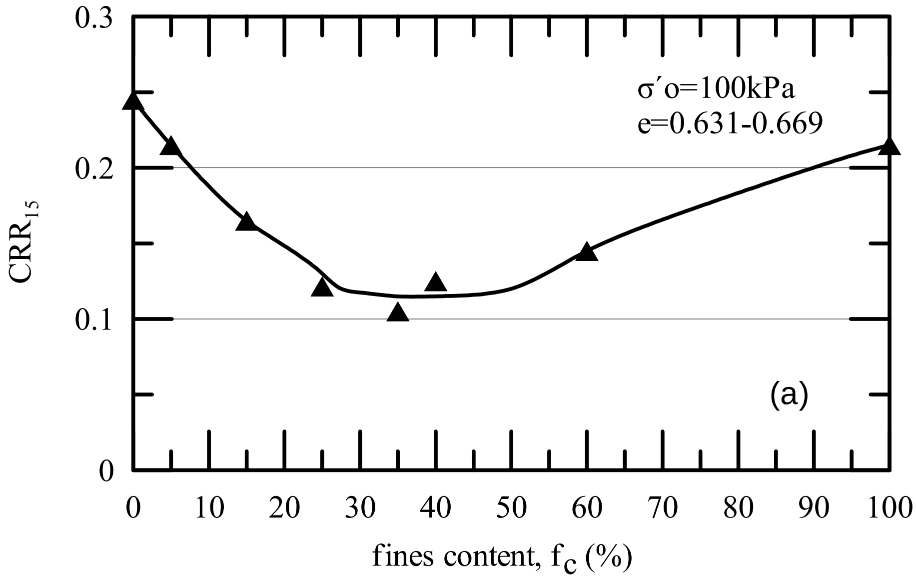


Figure 6. Variation of cyclic stress ratio, $\sigma_d/2\sigma'_o$, with number of cycles, N, at constant void ratio, e, and various fines conents, f_c, at σ'_o=100kPa (a) and σ'_o=300kPa (b)



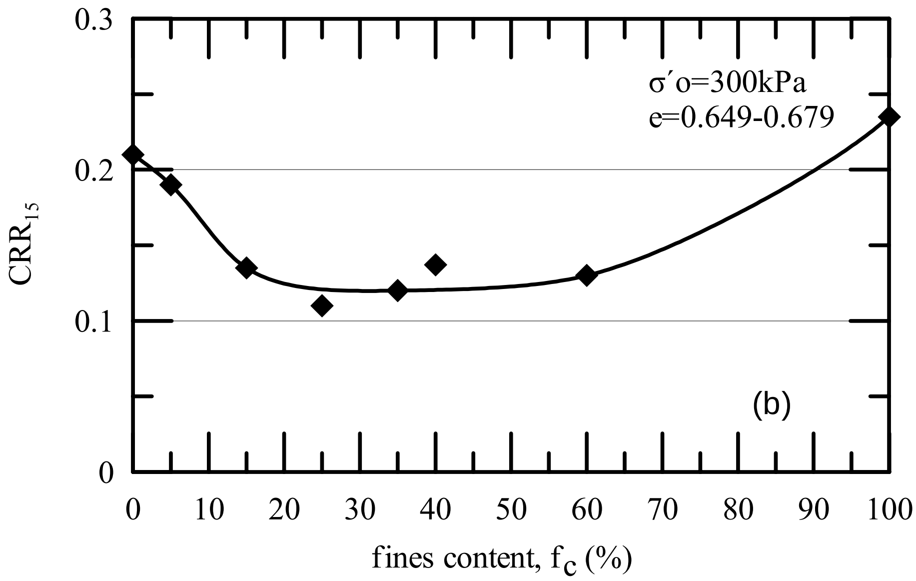


Figure 7. Effect of fines content, f_c on liquefaction resistance, CRR_{15}, at constant void ratio, e, at σ'_o=100kPa (a) and σ'_o=300kPa (b)

CONCLUSIONS

The following conclusions can be drawn regarding the effect of non-plastic fines on the liquefaction resistance of the tested sand and mixtures:

1. Liquefaction resistance decreases with increasing mean effective stress at a given void ratio and also with increasing void ratio at a given constant mean effective stress.
2. At constant void ratio, liquefaction resistance decreases with increasing fines content up to a threshold value, beyond this value liquefaction resistance remains relatively constant irrespectively of fines content, unless the latter is increased significantly. The threshold fines content depends on the mean effective stress level and the characteristics of sand and fines. For the tested materials is about 35% and 30% at mean effective stress 100 and 300 kPa respectively.

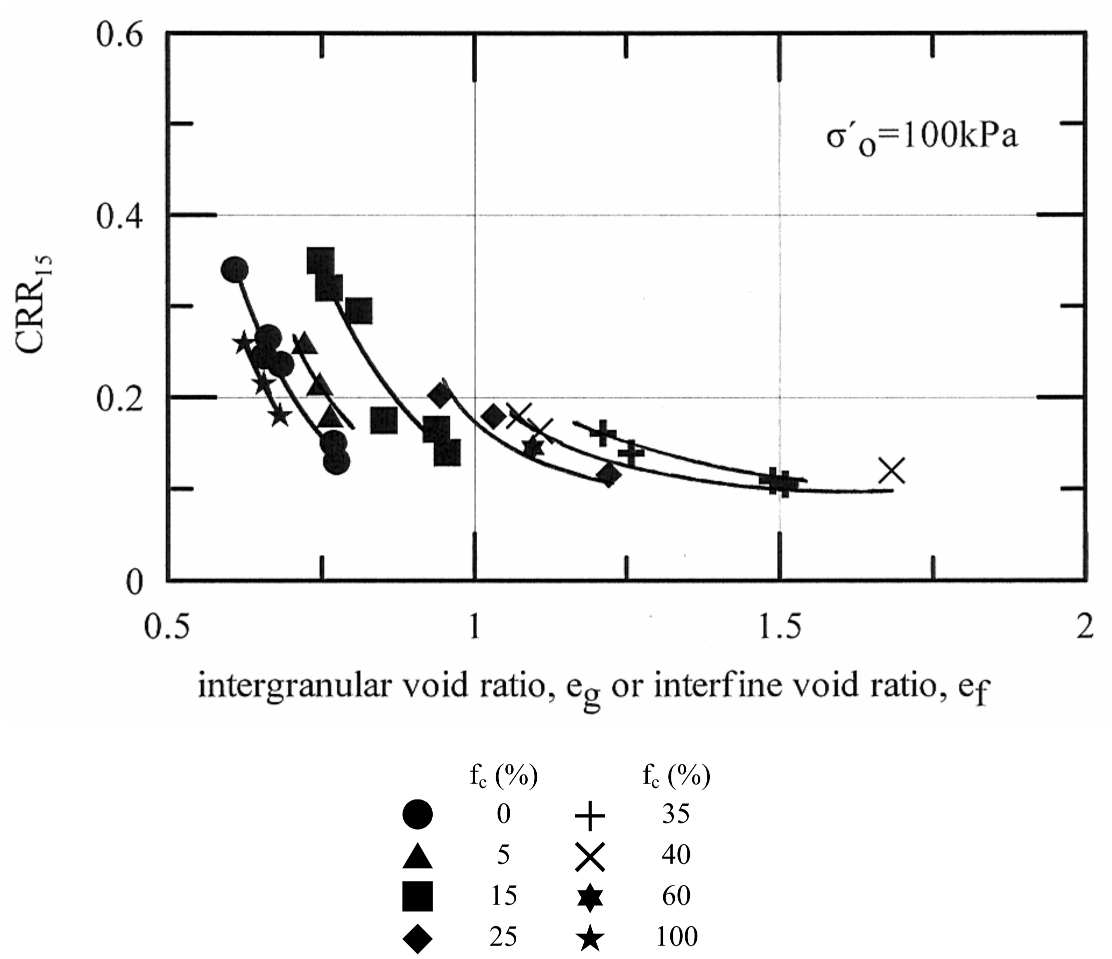


Figure 8. Variation of liquefaction resistance, CRR_{15}, with intergranular void ratio, e_g or interfine void ratio, e_f, at various fines contents, f_c, (e_g for $f_c \leq 35\%$ and e_f for $f_c \geq 40\%$)

3. At constant intergranular void ratio, liquefaction resistance increases with increasing fines content. This positive effect of fines on liquefaction resistance is in agreement with that suggested in the semi-empirical procedures for evaluating liquefaction potential during earthquakes. For the SPT-based procedure, this agreement may indicate that a constant N_{SPT} value corresponds to a constant e_g value.

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