Evaluation of Liquefaction Susceptibility based on Peak Dilatancy and Particle Shape Characteristics

Évaluation de Susceptibilité de Liquéfaction basée sur le dilatance pic et Caractéristiques de forme des particules

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ABSTRACT: This study investigates the influence of soil dilatancy on liquefaction susceptibility. For this purpose, cyclic simple shear tests were conducted on clean sand samples prepared at different unit weight-vertical stress combinations. Tests were conducted on two different sand types and liquefaction susceptibility was defined in terms of the number of cycles of loading until liquefaction. In these tests, potential dilatancy of each sample was calculated empirically as a function of soil density and in-situ stress state. As the tests were repeated at different density-stress combinations, potential peak dilatancy and liquefaction susceptibility relationship was obtained for the soil under investigation. Obtained relationship was valid for the selected cyclic stress ratio and cyclic frequency. Then the tests were repeated at different combinations of cyclic stress ratio and cyclic frequency to quantify their influences on the dilatancy - liquefaction susceptibility relationship. Obtained results were used to investigate the influence of particle shape characteristics on liquefaction susceptibility.

RÉSUMÉ: Cette étude examine l'influence de dilatance du sol sur la susceptibilité de liquéfaction. A cet effet, des essais de cisaillement simple cycliques sont effectués sur des échantillons de sable propres préparés aux différentes combinaisons de poids volumétrique-pression verticale. Les essais sont effectués sur deux types de sable différents et la sensibilité de liquéfaction seront définies en fonction du nombre de cycles de chargement jusqu'à la liquéfaction. Dans ces essais, dilatance potentiel de chaque échantillon sera calculé empiriquement en fonction de la densité du sol et l'état de stress in situ. Comme les tests sont répétés en combinaisons différentes contraintes-densité, une relation de potentiel de dilatance pic et la susceptibilité de liquéfaction sera obtenu pour le sol sous l'analyse. La relation obtenue sera valable pour le rapport de contrainte cyclique choisi et la fréquence cyclique. Ensuite, les tests seront répétés à différentes combinaisons de rapport cyclique de pression et de la fréquence cyclique pour quantifier leurs influences sur la relation entre la susceptibilité de liquéfaction et dilatance. Les résultats obtenus seront utilisés aussi pour étudier l'influence des caractéristiques de forme des particules sur la susceptibilité de liquéfaction.

KEYWORDS: dilatancy, cyclic mobility, sand, K_0 consolidation, liquefaction susceptibility

1 INTRODUCTION

Liquefaction occurs when saturated loose cohesionless soils lose their initial stiffness and strength, as a result of increase of pore water pressure caused by undrained shear loading. (Kramer 1996). This phenomenon still remains as a widely investigated yet controversial and challenging topic in the geotechnical field. In literature, it is a commonly accepted fact that, increased dilatant properties helps soil to have greater liquefaction resistance. According to Youd (1977), because of packing rearrangements caused by cyclic loading, sandy deposit will go through a repetitive shear-dilation process, which leads to instances of pore pressure reduction where a regain in shear stiffness and strength occurs. However, owing to problems associated with the measurement of dilatancy angle in cyclic tests and the influence of stress path on dilatant behavior, effect of dilatancy on liquefaction susceptibility has not been clearly established. Thus, the main aim of this study is to investigate the link between potential dilatancy and liquefaction potential and also to suggest a simple method which would allow the computation of liquefaction susceptibility based on the dilatant potential of clean sands.

Dilatancy angle is a function of soil density and effective stress state and it varies with strain level. Additionally, the value of the dilatancy angle that influences soil behaviour is the peak dilatancy angle (Abadkon 2012). Since peak dilatancy angle can only be measured at the instance of failure, it is not possible to obtain this value in cyclic tests. Accordingly, this study attempts to overcome this difficulty by calculating the peak dilatancy angle from the initial density and effective stress state of the soil. A specially calibrated empirical equation (Cinicioglu & Abadkon 2014) is used for this purpose. The empirical equation calculates peak dilatancy angle relevant for conventional compression conditions. Here, the calculated dilatancy angle is a manifestation of the combined influences of packing density and stress state and is relatable to the state parameter defined by Been and Jefferies (1985).

K_0 consolidated-drained (CD) triaxial test were conducted in order to obtain the constants of the dilatancy equation and calculate peak dilatancy angles of the cyclic simple shear tests. Cyclic simple shear tests were conducted to measure the liquefaction resistance corresponding to different peak dilatancy angle values and they were repeated for different cyclic stress ratios and cyclic frequencies.

Literature review about cyclic simple shear testing shows that; research interest was focused on lower cyclic frequencies, mainly on 0.1 Hz, although this frequency is too low for a typical earthquake. Sriskandakumar et al (2012) state that the undrained behavior of sand is known to be essentially frequency independent and 0.1 Hz was commonly adopted as reasonable for cyclic loading of granular materials for laboratory work. This study also questions this common approach and uses higher frequencies, which are 1, 0.5 and 0.2 Hz.

On the other hand, particle shape characteristics and its impacts on liquefaction susceptibility are also studied in geotechnical literature. Dodds (2013) states that global form or shape of a sand particle is at first determined during formation and later by the effects of weathering. Vaid et al. (1985) compared sands with the same gradation and different angularity. It was suggested that liquefaction susceptibility for rounded sand was higher than for angular sand at low confining pressures. Cho et al. (2006) concluded that increasing angularity resulted in increase in critical state friction angle. Cox (2008) used both light microscope and scanning electron microscope for the determination of particle shape characteristics and suggested that the differences between the results of two microscopes did exist however were not significant.

In this study, particle shape characteristics were determined using image processing software and average circularity and roundness values of three different sand types were examined. Moreover, the effect of these factors on overall test results are discussed.

2 EXPERIMENTATION

2.1. *Sample preparation, sand and particle shape properties*

In this study, three local Istanbul sands were used. Gradation curves of two poorly graded sand types from Kilyos and Akpinar region and relatively well graded sand from Sile region according to ASTM standards can be found in Figure 1. Properties of the sands are given in Table 1.

Following the law of large numbers, analysis of 50 particles is sufficient to obtain the mean values of circularity and roundness shape parameters (Ranjpour 2015). Accordingly, 50 random individual particles were examined for both Kilyos, Sile and Akpinar sands. Average values for shape parameters and basic properties of sands under investigation are given in Table 1.

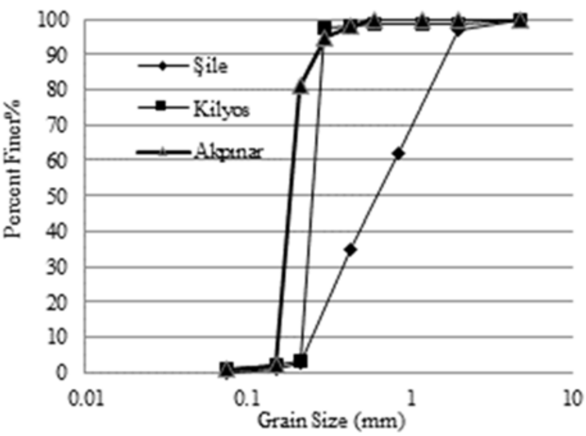

Figure 1 Grain Size Distribution Curves

Table 1 Properties of Sands under Investigation

Properties	Kilyos	Sile	Akpinar
Specific Gravity	2.66	2.61	2.63
Maximum Void Ratio	0.77	0.78	0.87
Minimum Void Ratio	0.44	0.52	0.58
Uniformity Coefficient	1.17	3.20	1.19
Curvature Coefficient	0.93	0.76	0.95
Circularity	0.61	0.56	0.58
Roundness	0.77	0.76	0.73
α_ψ	-0.00065	-0.07111	-0.0662
m_ψ	0.62639	0.46653	0.649
Critical state friction angle (ϕ'_c)	33.3°	32.9^0	33^0

Throughout this study, dry clean sand samples were prepared using air pluviation method. Air pluviation is achieved by allowing dry sand to fall through a funnel from a predetermined height. This height is adjusted to keep the distance of raining constant throughout the sample preparation phase in order to obtain uniformity throughout the sample. Samples with higher relative densities were achieved by increasing the height of fall and reducing the rate of fall (Towhata 2008).

2.2. *Dilatancy angle calculation based on in-situ soil conditions using triaxial test results*

Cinicioglu and Abadkon (2014) proposed the following empirical equation for predicting the peak dilatancy angle (ψ_p) as a function of initial density and stress state of the sample.

$$\tan\psi_p = \alpha_\psi\left(\frac{p'_i}{p_a}\right) + m_\psi I_D \tag{1}$$

According to Equation 1, p'_i is the pre-shear mean effective stress, I_D is pre-shear relative density and p_a is the atmospheric pressure. α_ψ and m_ψ are both empirical constants that can be obtained by triaxial test results. Magnitudes of α_ψ and m_ψ for Kilyos and Sile sands, are obtained from the results of sixteen K_0 triaxial compression tests, are reported in Table 1. α_ψ, m_ψ and ϕ'_c values for Akpinar sand, were already determined by Altunbas (2015), by the exact same method and therefore were used in this study.

2.3. *Liquefaction Susceptibility Analyses Based on Cyclic Simple Shear Test Results*

Fully automated Geocomp ShearTrac II is used for cyclic simple shear tests. Finn and Vaid (1977) stated that, in a constant volume test, the pressure reduction during cyclic loading can be taken as equivalent to the increase in pore water pressure that would occur in a corresponding undrained test. Dyvik et al. (1987) also worked on constant volume tests and measuring the pore water pressure. Overall results showed that the results are very similar to truly undrained nature. In order to simulate undrained soil conditions, constant volume cyclic simple shear tests (CSS) were conducted.

Each cyclic simple shear test has two phases, namely consolidation phase and cyclic shearing phase. In pursuance of investigating the relationship extensively, tests were conducted under 18 different combinations of cyclic stress ratios (CSR), cyclic frequencies (CF) and consolidation pressures. CSR is defined as the ratio of cyclic shear stress applied during the shearing phase to vertical effective stress (σ'_{vc}) at the end of consolidation phase. CF is simply the frequency of loading cycles. In these combinations, CSR values were taken as 0.2 or 0.3, CF values were taken as 1 Hz, 0.5 Hz or 0.2 Hz and consolidation pressures were taken as 50 kPa, 100 kPa or 200 kPa.

More than 250 constant volume cyclic simple shear tests (CSS) were conducted. In order to calculate the potential peak dilatancy angles of the samples tested in cyclic simple shear tests, it is necessary to know the value of pre-shear mean effective stress (p'_i). This requires knowledge of the value of the coefficient of lateral earth pressure (K_0). For this purpose, variations of K_0 with relative density for both sands were obtained from the results of K_0 triaxial tests and relationships were defined between K_0 and I_D.

Since the samples were prepared using air pluviation method, relative density values differ from sample to sample, ranging between 35% up to 85%. For every cyclic simple shear test, plugging the value of relative density (I_D), pre-shear mean effective stress (p'_i) and sand characteristics (α_ψ and m_ψ) in Equation 1, yields the tangent of peak dilatancy angle ($\tan\psi_p$) relevant for conventional triaxial compression tests.

In the cyclic simple shear tests the samples were considered to liquefy when either one of the following conditions are met: pore pressure ratio ($r_u = u/\sigma$) reaches 100% or the double amplitude cyclic shear strain reaches 7.5%.

General trends of the tangent of ψ_p versus number of loading cycles to liquefaction relationships are linear as illustrated in Figure 2. Similar to Figure 2, all combinations lead to approximately linear relationships between number of cycles to liquefaction (NCL) and peak dilation angle. Thus, it can deduced as expected, increases in ψ_p results in greater liquefaction resistance.

3 RESULTS & DISCUSSION

3.1. *Effect of initial vertical effective stress on liquefaction susceptibility*

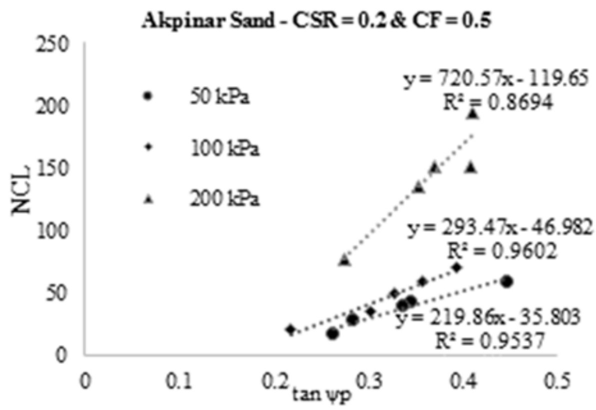

Figure 2 tan ψ_p – NCL relationships for tests with CSR=0.2 & CF=0.5 for Akpinar Sand

In order to monitor the influence of vertical effective stress on test results, tan ψ_p – NCL relationships obtained from testing Akpinar sand under 50 kPa, 100 kPa and 200 kPa with a CSR = 0.2 and CF = 0.5 can be compared by using Figure 2. As it can be seen from the results, the tests with higher initial vertical effective stresses have greater liquefaction resistance as evidenced by the higher NCL values. According to Ranjpour (2015), the key factor to explain the effect of σ'_{vc} is the pore water pressure generation. For the specimen to liquefy, pore water pressure should increase until it reaches to the consolidation pressure value which results in zero vertical stress. This means greater the consolidation pressure, greater the value of NCL. That is why NCL values are relatively greater for tests which are conducted under greater vertical stresses, even though they have the same dilatancy angle with tests under the action of smaller stresses.

3.2. *Effect of cyclic frequency on liquefaction susceptibility*

To be able to identify the influence of CF on liquefaction susceptibility, tan ψp – NCL relationships of Kilyos sand under 50 kPa, 100 kPa and 200 kPa and same CSR value can be examined. Figure 3 compares all nine CSR = 0.2 combinations of Kilyos sand and shows that, decrease in cyclic frequency causes decrease in liquefaction resistance.

This is attributed to the fact that for lower cyclic frequencies, the samples have longer times to rearrange their granular structures, which results in faster increase of pore water pressure.

Figure 3 also enables to see the similarity between the responses of Akpinar (Figure 2) and Kilyos sands towards the changes in initial vertical effective stresses.

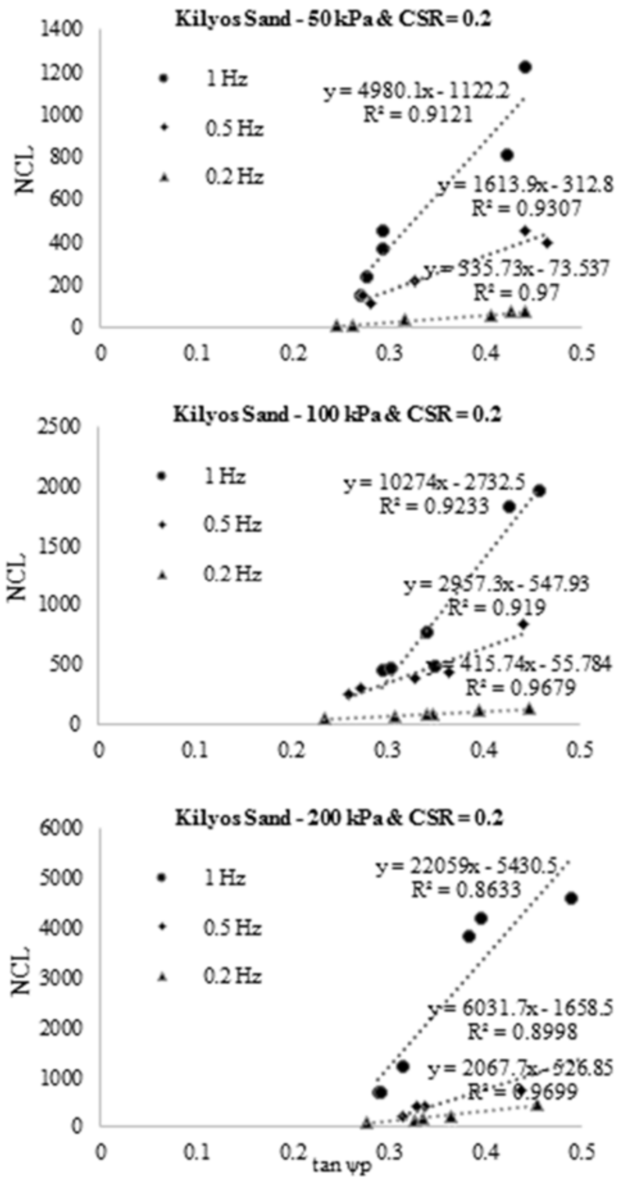

Figure 3 tan ψ_p – NCL relationship for tests with CSR = 0.2 for Kilyos Sand

3.3. *Effect of cyclic stress ratio on liquefaction susceptibility*

In order to see the CSR effect clearly, it is important to examine the test results by keeping the cyclic frequency constant. The best indicator for comparing the influences of different factors on liquefaction resistance is to compare their effects on the gradients of the best-fit line equations. As it can be seen in Figure 4, NCL values are significantly higher for tests conducted with lower cyclic stress ratios. This outcome is expected, as loading with lower cyclic shear stresses requires greater number of loading cycles to reach liquefaction. Comparing the gradients in Figure 3 and Figure 4, it is deduced that the effect of change in CSR is more dominant on the results than the effect of change in CF.

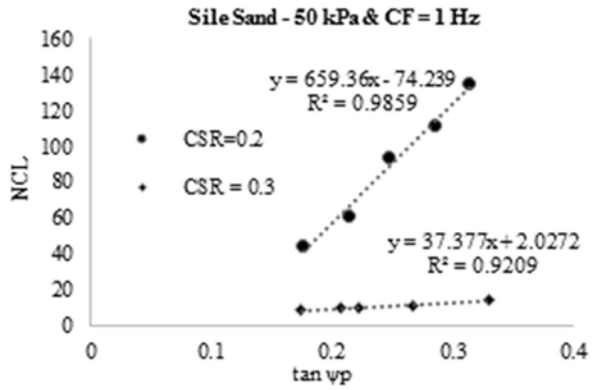

Figure 4 tan ψ_p – NCL relationship for tests with 50 kPa & CF=1 Hz for Sile Sand

3.4. *Comparison of behaviour of three different sands*

Analyzing the line equations of all 18 combinations of cyclic simple shear tests for three sands shows that, in every case, Kilyos sand is most resistant to liquefaction.

For all sands in this study, tan ψ_p – NCL relationships are more influenced by the changes in CSR rather than changes in CF. However this does not mean that the relationships are frequency independent, although this is generally accepted by the current literature for cyclic behavior of sands in cyclic simple shear testing. For all three sands under investigation, increase in cyclic frequency led to an increase in liquefaction resistance.

It is not possible to come to a definitive conclusion by only comparing the results of dilatancy behaviors of Kilyos and Sile sand, since both shape parameters and gradation curves differ for each sand. However it should be noted that; although Sile sand is relatively well graded and has a less circular nature, it is less resistant to liquefaction when compared to Kilyos sand.

Akpınar and Kilyos sands have similar gradation curves and uniformity and curvature coefficients, while their particle shape parameters differ. Kilyos sand has higher circularity and roundness values in comparison to Akpınar Sand. The overall results show that Kilyos sand is more resistant than Akpınar. This result can suggest that increasing circularity can result in an increase in liquefaction resistance.

4. CONCLUSION

With the aim of investigating the relationship between dilatancy, cyclic mobility and average particle shape, 16 K_0 CD triaxial tests and over 250 cyclic simple shear tests with three sand types were conducted. Dilatancy constants for predicting the peak dilatancy angles and K_0 – relative density relationships were obtained from the results of the triaxial tests. 50 particles of each sand type was processed and average circularity and roundness values were found using an image processing software. Since 18 different combinations of variables were used in cyclic simple shear tests, the individual impacts of consolidation pressure, cyclic stress ratio and cyclic frequency on relationships of peak dilatancy versus liquefaction susceptibility for each sand type were presented. Moreover, the behavior of three different sand types was compared and the reason behind the difference were investigated.

Additionally, it is also noted that although commonly accepted in the literature, liquefaction resistance is not frequency independent. In this study, there frequencies (0.2, 0.5 and 1 Hz) were used, with the aim of a better simulation the earthquake field conditions. In every case, change in frequency led to a change in the tan ψ_p – NCL relationship.

Finally, considering the tests with the same cyclic stress ratio and cyclic frequency combinations, it was observed that the peak dilatancy-liquefaction resistance relationships can be practically considered linear.

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