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LABORARTORY INVESTIGATION OF THE EFFECT OF PLASTIC FINES ON CYCLIC RESISTANCE OF SAND-CLAY MIXTURES

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ABSTRACT

This paper investigates the effects of plastic fines on the behavior of Firouzkooh sand (No.161) using liquefaction resistance as a comparative parameter. Two sets of triaxial cyclic tests were conducted using different plastic fine contents and different plasticity indexes. The plastic fines were kaolin and bentonite. The first set of tests was performed by adding 10, 20, 30, 40, and 50% of kaolin to sand at a mean effective confining stress. In order to be able to compare the results, reconstituted samples with different kaolin content were tested at the same void ratio. It was found that by increasing the fines up to 30%, the liquefaction potential increased; whereas, with the addition of more fines it decreased. In addition, the effect of plastic fines on the excess pore pressure ratio (r_u) and ductility of the mixture was studied. In the second set of tests the plasticity of fines were changed by combing different proportions of kaolin and bentonite. It was found that as the plasticity of the fines increased, the liquefaction potential decreased. Finally, a study involving the scanning electron microscope (SEM) was also carried out in conjunction with the test program to assist in the development of a rational framework to explain the observed behavior of mixtures.

Keywords: Firouzkooh Sand, Sand-clay mixtures, Fine content, Plastic Fines, Cyclic resistance, Liquefaction.

INTRODUCTION

Earthquake induced liquefaction is a major cause of loss in soil strength and consequent damage to soil-structure systems. Although, loose, saturated cohesionless soils are most susceptible to loss of strength, there is strong evidence suggesting that soils containing fines such as silty sands and clayey sands are also prone to liquefaction during earthquakes. For instance, The Chi Chi earthquake (Mw=7.6) of September 21, 1999 triggered extensive soil liquefaction in Central Western Taiwan. The majority of the sand deposit in this region was relatively compressible and had significant amounts of low to medium plastic fines (Chu et al., 2004). Likewise, in Adapazari, Turkey, hundreds of buildings settled, tilted, and collapsed during the August 17, 1999 Kocaeli earthquake (Mw=7.4) due in part to liquefaction and ground softening. Most of the soils in Adapazari contain significant fines (Bray et al., 2004)

Experience has indicated that mineral contents and plasticity of the fines are important contributing factors to the monotonic or cyclic behavior of sands that contain fines (Ishihara, 1993). The effects of plastic or non plastic fines on the behavior of sand have been a subject of geotechnical research for

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many years. These studies, however, have not lead to a consensus as to whether fines can increase or decreases the undrained strength or cyclic resistance of sands as described by Polito (1999).

The experimental data related to the effect of plastic fine content and their plasticity on the behavior of sand-fine mixtures is limited because most prior studies have focused on clean sands or sands with non-plastic fines. Georgiannou et al (1990) investigated the undrained behavior of Ham river sand mixed medium plastic kaolin clay. They found that the presence of clay fractions up to 20% in a mixed soil did not reduce the angle of shearing resistance at critical state, but reduced the stability of the fabric of sand, causing a reduction in undrained shear strength at quasi-steady state. In a study on the liquefaction potential of silty sands, Kaufman (1981) found considerable increase in cyclic shear resistance of soils due to the presence of moderately plastic fines. Koester (1994) made a detailed description of the results of about 500 stress-controlled cyclic triaxial tests on isotropically consolidated specimens. He found that the cyclic strength of the mixture decreases with addition of fines up to about 20% to 30% fines content; thereafter, it starts to increas. Regarding the plasticity of the fines he found that low plasticity index, of the order 4, was associated to the lowest values of the cyclic strength; slight but continuous increases of the strength was observed for PI=10 and higher. Pitman et al (1994) investigated the effect of plastic and non-plastic fines on the monotonic behavior of Ottawa sand. Their findings indicate that by increasing fines content, the amount of structural instability was decreased. Moreover, the location of steady-state line changed with changes in the percentages and plasticity of the fines and the 20% fines content marks the transition between a sand-dominated mixture and a fines-dominated matrix. Kuwano et al (1995) studied the undrained monotonic and cyclic shear behavior of sand-kaolin mixtures. They found that when the clay is mixed with sand, the peak and the residual strengths of clayey sand decreases with the increases in the clay content up to about 20%. With the further increase in the clay content, the strengths of sand kaolin mixture increased. In addition, the cyclic strength was lowest at a kaolin content of 20% and increased gradually when it reached 40%. Ni et al (2004) investigated the effect of plastic and non plastic fines on the behavior of sand-fine mixtures. They found that silt-size quartz and kaolin fines contribute differently to the mechanical properties. The examined results indicated that in a normally consolidated state, plastic fines have more negative effect than just occupying the voids, whereas in an overconsolidated state they behave just like voids. On the other hand, Non-plastic silt sized quartz appears to contribute to the strength.

To study the behavior of sands under the influence of varying fines contents and different plasticities, undrained cyclic triaxial tests were performed on reconstituted samples with various percentages of plastic fines (< 74μm) added to Firouzkooh sand no.161. A study involving the scanning electron microscope (SEM) was also carried out in conjunction with the test program to assist in the development of a rational framework to explain the observed behavior of mixtures

MATERIAL PROPERTIES

The sand used in the testing program is Firouzkooh sand (no.161) which is a medium to fine sand with a mean grain size (D_{50}) of 0.27 mm. The coefficient of uniformity and coefficient of curvature are 1.87 and 0.88, respectively. The maximum and minimum void ratios are 0.943 and 0.541, respectively. The plastic fines were kaolin and bentonite. Liquid limit and plastic limit of kaolin are 38% and 19% respectively. Also, bentonite has a liquid limit of 112% and a plastic limit of 64%. Grain size distribution curves of sand, kaolin and bentonite are shown in fig.1.

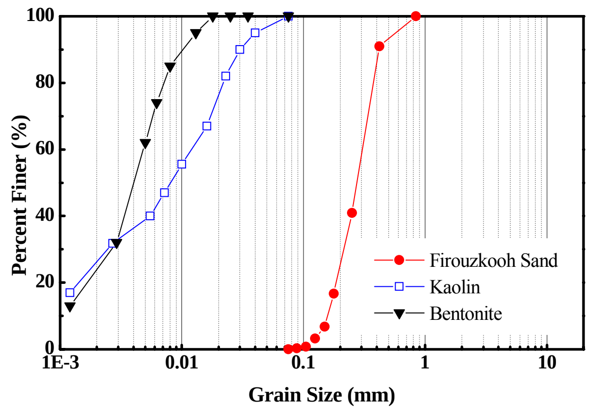

Figure 1. Grain size distribution of sand, kaolin , and bentonite

EXPERIMENTAL STUDY

Kaolin was mixed with sand in proportions of 0, 10, 20, 30, 40, and 50 percent by weight. The control parameter was chosen as the void ratio because the values of maximum and minimum void ratios, e_{max} and e_{min}, of sand-fines mixtures have been found to depend on fines content (Thevanayagam, 2000 and Thevanayagam et al., 2000). It was also recognized that according to standard methods described in ASTM D4253 (1) and ASTM D4254 (2), relative density can only be determined for granular soils with less than 15% by weight of non-cohesive fines. For this reason, the relative density of sand-clay mixtures cannot be consistently determined. Therefore, global void ratio has been chosen as a constant parameter in all tests in order to compare the undrained shear strength and other soil behavior indexes under a given state. In this approach, only specimens that met this specific criterion were considered in the analysis. The specimens were prepared to a constant post consolidation void ratios of 0.58 to 0.61. In order to isolate the effects of fines plasticity, specimens were prepared to a constant fine content of 16 percent with varying fines compositions presented in table 1.

Table 1. Atterberg limits of mixtures

Kaolin content	Bentonite content	Total Fine Content	Liquid Limit	Plasticity Index
16	0	16	38	19
12	4	16	54	25
8	8	16	67	33
4	12	16	101	41

SAMPLE PREPARATION AND TEST METHOD

The most used methods for reconstituting samples include moist tamping, water sedimentation and dry deposition. In this study, taped dry deposition method through a funnel with a zero height of fall was used to prepare samples. The host sand was mixed thoroughly with the kaolin to form a homogeneous mixture. Specimens were prepared by placing mixture in a funnel that had a tube attached to the spout. The tube was placed in the bottom of a split mold and was then slowly raised along the centerline of the specimen; such that the clayey sand is deposited without any drop height .The target void ratio was achieved by controlling the total weight of the soil mixture and by tapping the mold gently in a symmetrical pattern, as necessary. The diameter of specimen was measured after a slight vacuum was applied and the mold was removed. Both the diameter and height of the specimen was measured to the nearest 0.01 mm. The diameter was determined at three locations (top, middle and bottom) to ensure the specimen's quality. Specimens had a diameter of 38 mm and a height of 76 mm.

Saturation was performed by purging the dry specimen with Co_2 for approximately 45 min. De-aired water was then introduced into the specimen from the bottom drain line. Water was allowed to flow through the specimen until 100 cc of water was collected in a breaker through the specimen's upper drain line. A back pressure of 350 kPa was applied to all specimens and a minimum B-value of 0.96 was obtained for all tests. The decision to keep the value of back pressure constant in all tests was also based on data reported by Xia and Hu (1991) indicating an increase of liquefaction resistance with increasing values of back pressure. The time interval required to achieve saturation ranged from 1 h to 5 h, depending on the fines content of the tested soil. The saturated samples were consolidated isotropically with an effective confining stress of 200 kPa. The selection of this particular value for σ'_3 in cyclic tests was based on the fact that many cyclic triaxial test results under similar value of σ'_3 are available in the literature. In order to minimize volumetric creep and maintain a normally consolidated state, shearing was commenced as soon as initial consolidation was achieved. A sinusoidal varying deviator stress at the appropriate Cyclic Stress Ratio (CSR) with a frequency of 0.05 Hz was performed in compression-extension mode.

Following the completion of the test, the specimen was collected to determine its water content and consequently its void ratio. It should be noted that the Gs was calculated regarding the percent of each material present in the mixture.

UNIFORMITY OF SAMPLES

It is known that the specimen preparation method or soil fabric have significant effects on the stress-strain relationship and cyclic strength of sands (Ishihara, 1993) The situation is more complicated for clayey sand as it involves additional issues of soil compressibility and particle segregation. The quality of specimen in terms of the variation of clay content along its height was checked. Specimen with various clay contents were saturated and back pressured as described earlier. Upon saturation and consolidation to an effective confining stress of 200 kPa, the specimen was removed from the triaxial cell and sliced horizontally into four equal layers, numbered 1-4 from top to bottom. For each slice, the clay content was determined by washing on a 74 μm sieve. Table 2 shows the results and statistics of the samples. The results showed that the variation of clay content within the specimen was in an acceptable range.

Table 2. Fines content distributions within soil specimens

Target Clay Content	Level 1	Level 2	Level 3	Level 4	Mean	Standard Deviator
10	10.23	8.56	9.87	10.85	9.87	0.840
20	20.56	20.35	20.86	18.89	20.35	0.910
30	29.87	30.67	30.13	29.45	30.03	0.442
40	41.65	40.12	40.97	39.32	40.51	0.877

RESULTS AND DISCUSSION

Effect of Clay Content on Cyclic Resistance

Figure 2 presents the relationship between cyclic stress ratio and clay content for constant values of void ratio (0.58-0.61). It is observed that the liquefaction resistance decreases with the addition of plastic fines up to a fine content of 30%. Beyond this critical value, the trend is reversed and the liquefaction resistance increases with increasing fines content. The same trend has been reported for non-plastic fines in a constant value of void ratio (Polito and Martin, 2001, Xenaki and Athanasopoulos 2003, Yang et al 2006). According to Seed et al (2003) this Threshold Fine Content

(TFC) typically occurs as the fines content exceeds about 15% to 35% and it depends principally on the overall soil gradation and the characteristics of the fines. As a case in point, well-graded soils have lesser void ratios than uniformly-graded or gap graded soils, and so require lesser fines contents to fill the remaining void space and thus separate the coarser particles. Polito (1999) performed a brief analysis of the TFC from 37 sands and five silts, and concluded that for most of the silty soils, this TFC is between 25 and 45%.

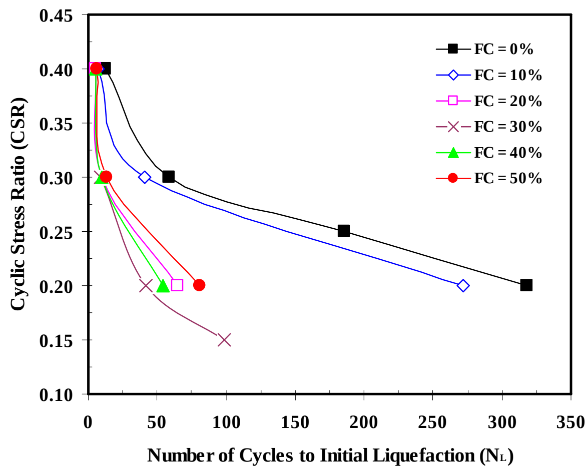

Figure 2. Effect of fines content on liquefaction resistance of sand-kaolin mixtures for constant values of void ratio

The diagram of Fig 3 shows the CRR versus clay content. CRR was defined as the $\sigma_d/2\sigma'_c$ that produced a state of initial liquefaction ($u=\sigma_3$) in 15 cycles on uniform loading. In this figure, the existence of a critical value of fines content is clearly demonstrated. This critical value separates the range in which the liquefaction resistance decreases with increasing fines content from the range in which the behavior is reversed. The experimental results of this study indicate that this threshold value of fines content is, approximately, around 30%. The reason for sudden decrease of liquefaction resistance from 10% to 20% of clay is that at low amounts of clay (around 10%); most of the fines are occupying the voids between sand grains. By increasing the clay content up to 20%, some of the finer particles may also occupy locations near the contact points between the sand grains and can hold the sand grains slightly apart. This phenomenon will be discussed in section 6.

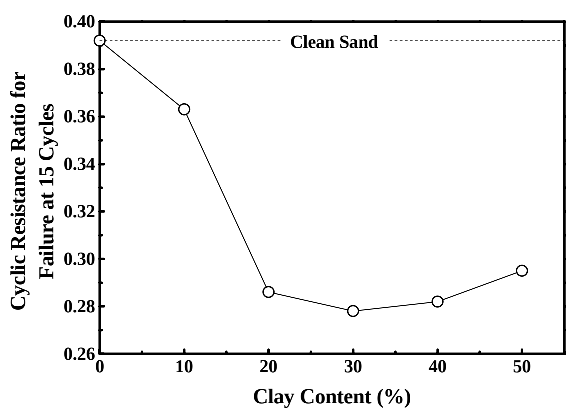

Figure 3. Effect of fines content on liquefaction resistance of sand-kaolin mixtures for constant values of void ratio

Effect of Clay Content on Ductility

Figure 4 shows the number of cycles required to cause initial liquefaction (N_L) and double amplitude axial strain of 5% ($N_{5\%}$) versus clay content for a cyclic stress ratios (CSR) of 0.3. By increasing the clay content, the failure defined by 5% axial strain occurs at relatively smaller cycles than those required to develop a state of initial liquefaction ($u=\sigma_3$). This implies that the behavior of the specimen becomes more ductile by increasing clay content. One possible explanation for this behavior is that as the clay content increases, contacts between sand particles decrease and the dominant phase of specimen changes from sand to clay; hence, the criterion of 5% double-amplitude axial strain is more convenient than initial liquefaction to define liquefaction of soils with high fine contents in cyclic triaxial tests, as reliable pore pressure measurements are difficult in cyclic testing with relatively low permeabilities as stated by El Horsi et al. (1984) and Das et al (1999).

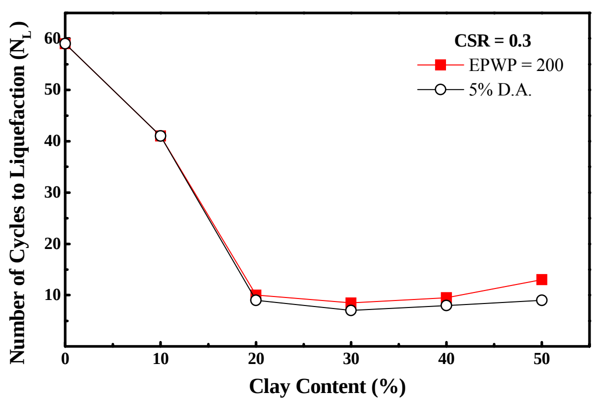

Figure 4. Effect of fines content on liquefaction resistance of sand-kaolin mixtures for constant values of void ratio for CSR = 0.3

Effect of Clay Content on Pore water Pressure Buildup

The main mechanism associated with the phenomenon of liquefaction is the generation of excess pore pressure under undrained loading conditions. Thus, in order to gain insight to the effect of fines outlined in previous sections, typical results demonstrating the general trend of the effect of fines content on the rate of pore pressure generation for a constant value of global void ratio are shown in Fig. 5. This figure presents rate of excess pore water pressure buildup ($\Delta u/\sigma_0$') versus clay content with CSR of 0.2. It is seen that the pore pressure generation rate for samples with 0%, 10% and 20% clay content is lower at the beginning of the cyclic loading compared with that of higher clay contents. This is due to the fact that the presence of high clay content distorts the granular structure and causes loosely packed groups of particles. With the application of cyclic loading, these loose particles collapse and will cause an increase in pore pressure between grains. The elimination of local instabilities at the contact points produces a more stable structure, which results in an almost constant rate of increase in the pore pressure build up. Consequently, the shape of rate of excess pore water pressure buildup graphs become similar for clay contents of 30%, 40% and 50%. The inconsistent trend for the curve with 10% fine needs to be studied further.

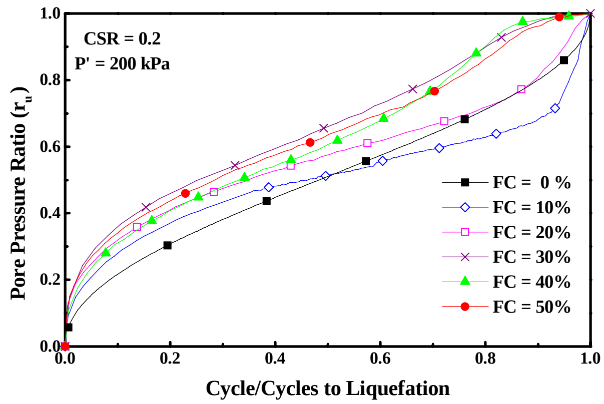

Figure 5. Effect of fines content on rate of pore pressure buildup of sand-kaolin mixtures for constant values of void ratio, CSR = 0.2

Influence of Effective Confining Pressure on Cyclic Resistance of Mixtures

The effect of confining pressure on cyclic resistance of mixtures is demonstrated in the diagram of fig.6. This diagram clearly depicts that the cyclic strength decreases as the confining pressure is increased from 50 kPa to 200 kPa. The same trend is reported by Hyodo and Aramaki (2001). One explanation for this trend is that as the confining pressure increases, the contractive tendency of the specimen increases resulting in generation of more excess pore water pressure which is the main mechanism associated with the liquefaction.

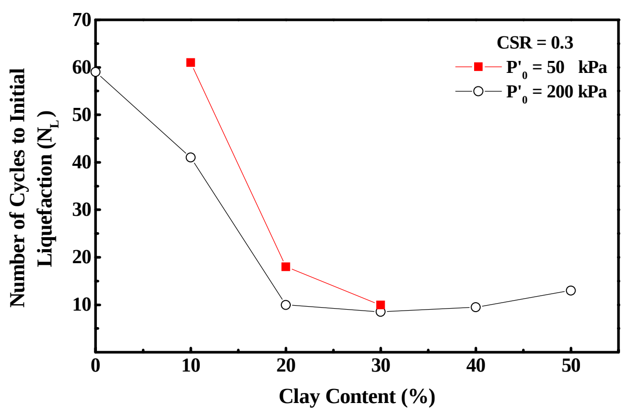

Figure 6. Effect of confining pressure on liquefaction resistance of sand-clay mixture for constant values of void ratio, CSR = 0.3

Effect of Plasticity of the Fines on Cyclic Resistance

While the small quantity of data makes it difficult to draw firm conclusions about the effect of plasticity index on cyclic resistance, it may be seen in fig.7 that increased plasticity index appears to result in an increase in cyclic resistance. In cohesive soils, the strength against liquefaction does not rely on friction between particles only, but cementation of particles together by electrical and chemical forces plays an important role, which increases with increasing plasticity (Perlea, 2000). This is in contradiction with the findings of Koester(1994) who claimed that the plasticity index of fines is less important than the fines content itself, but is in agreement with Ishihara(1993), Prakash and Guo(1999) who claim that the fines with high plasticity may fundamentally change the mechanism of excess pore pressure buildup. Ni et al (2004) found that the mineralogy of the fines has an important effect on their contribution on the behavior of sand-fine mixtures.

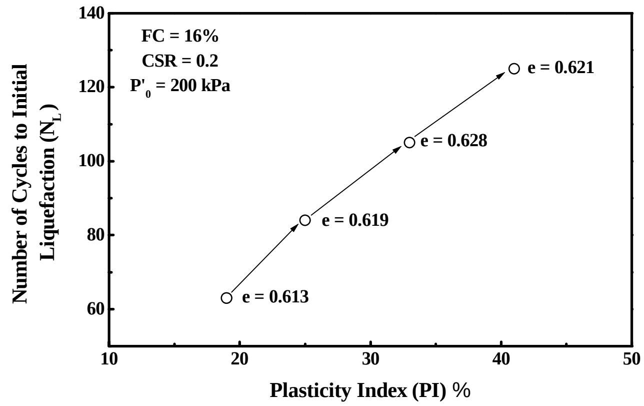

Figure 7. Effect of plasticity of the fines on liquefaction resistance of sand-kaolin mixtures for fine content of 16% and CSR = 0.2

SEM IMAGE ANALYSIS

In order to get a good understanding about the particle arrangement, the interaction of sand grains and clay particles, and surrounding void spaces on a microscopic level, a series of scanned electron microscope (SEM) images were prepared from the samples with different clay contents, shown in figures 8 to 13. Images on the right side depict the white bordered rectangular on the left, except for figure 13. It should be noted that for the specimens with 40% clay content, images are taken using a different SEM instrument. Figure 8 presents the specimen with 10% clay content. The image clearly illustrates that the clay particles are either fully confined within the void spaces between the sand grains or residing on the surface of sand grains; thus, the sand grains are in direct contact with each other and can effectively contribute in the load bearing chain. A distinct change is observed for specimens with 20% clay content (Fig.9). Clay particles are not only filling the void spaces between the sand grains, but also surrounding the sand grains. However, the sand grains are still in contact and dominate the overall behavior of the mixture. Figures 10, 11 and 12 present the images of specimens with 25%, 30% and 40% clay content, respectively. It is clearly evident that although the sand grains are gradually being confined with the clay particles, there are still sand grain to sand grain contacts. However, the numbers of such contacts are diminishing by increasing the clay content until the specimen with 40% clay (Fig.13) in which a sand grain to sand grain contact hardly shows up and the clay particles have fully confined the sand grains. The apparent distance between some sand grains have been shown. Therefore, from the microscopic point of view, the specimen with 40% clay content is a clay-dominated mixture and behaves as a clayey sample.

CONCLUSIONS

The effect of plastic fines on liquefaction resistance of sand-clay mixtures was studied. It was found that with addition of fines up to 30%, the liquefaction resistance decreased. On the other hand, with further increase of fines to 40%, the liquefaction resistance increased. From the ductility point of view, it was found that the ductility of the mixtures increases with addition of fines such that the 5% double-amplitude axial strain criterion occurs earlier than the state of initial liquefaction. Therefore, the

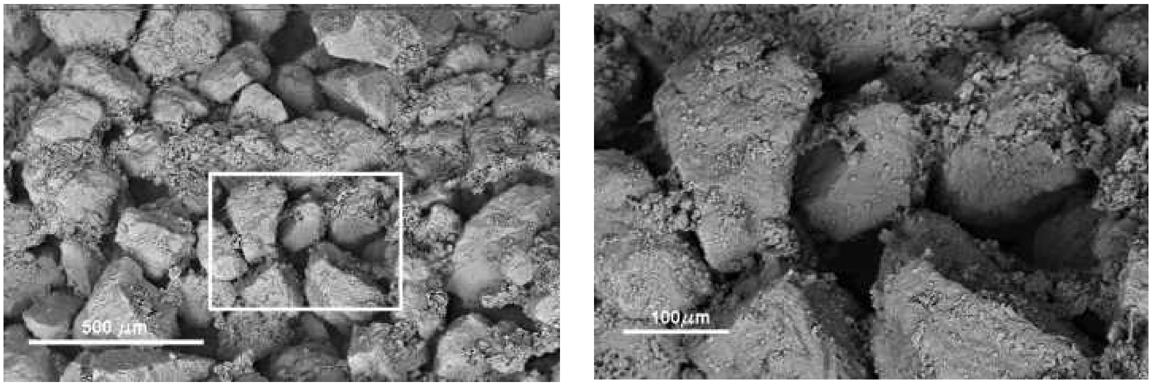

Figure 8: SEM image of sample with 10% clay

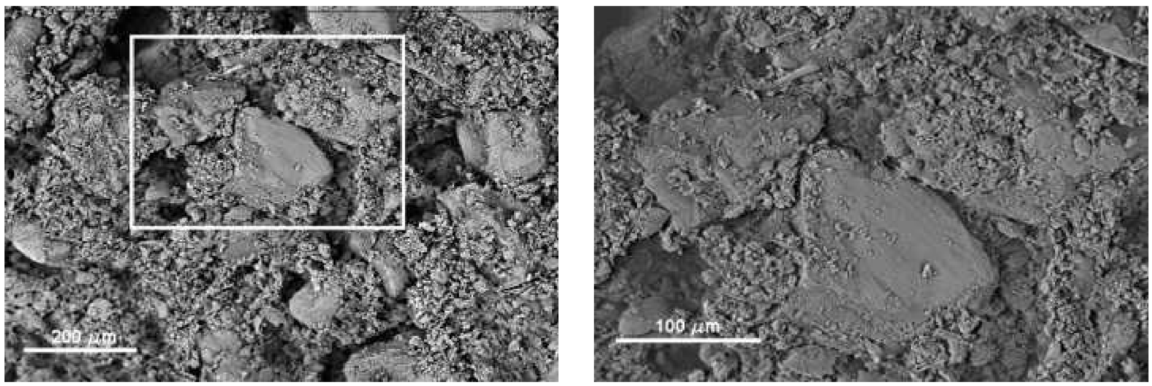

Figure 9: SEM image of sample with 20% clay

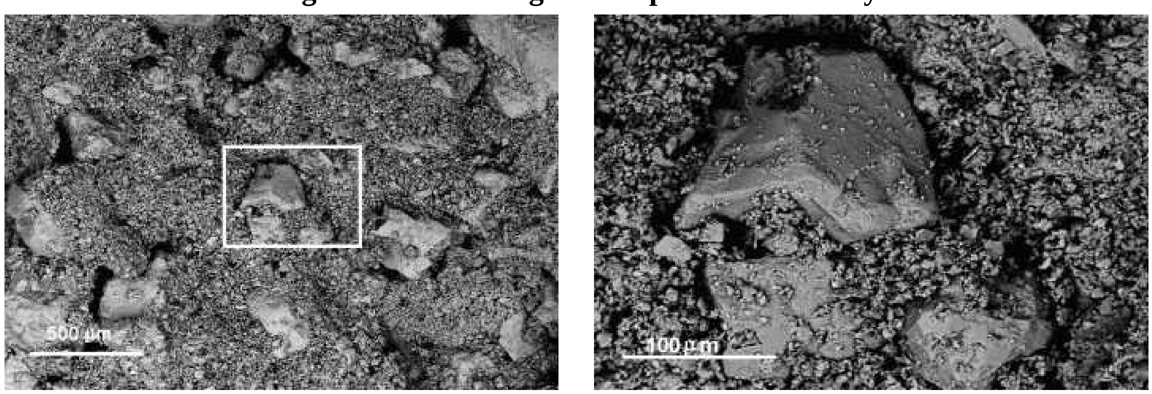

Figure 10: SEM image of sample with 25% clay

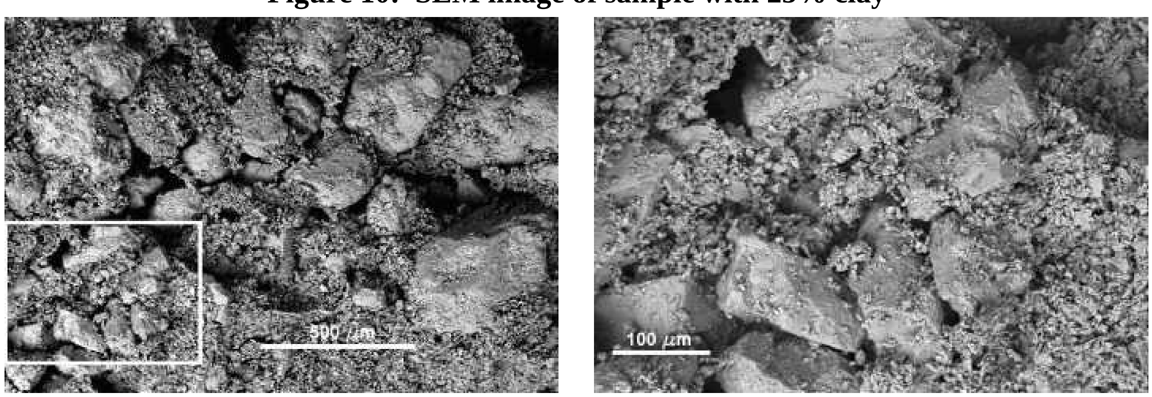

Figure 11: SEM image of sample with 30% clay

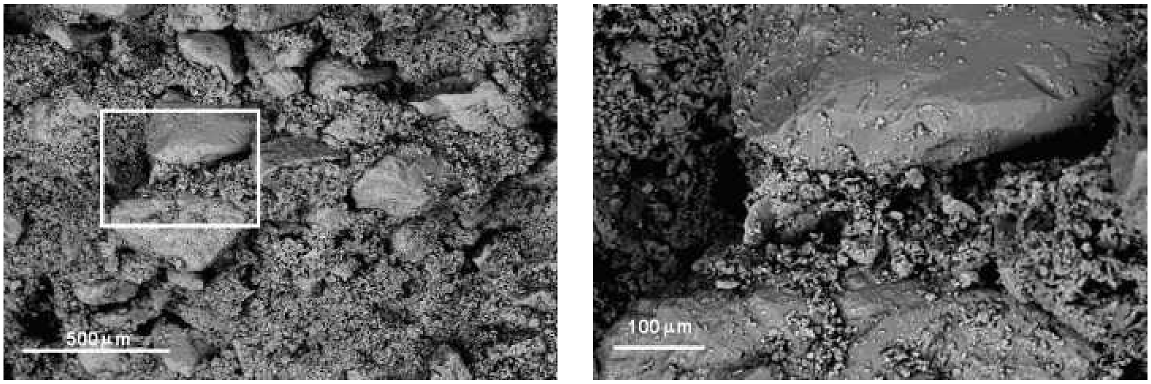

Figure 12: SEM image of sample with 35% clay

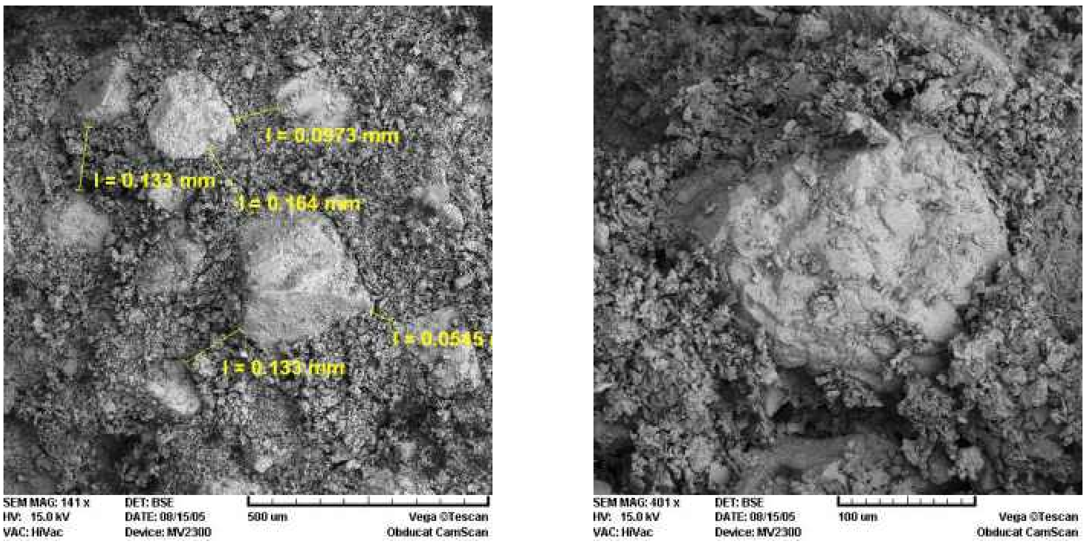

Figure 13: SEM image of sample with 40% clay

criterion of 5% double-amplitude axial strain is more convenient than initial liquefaction to define liquefaction of soils with high fine contents in cyclic triaxial tests. Besides, the influence of effective confining pressure was studied and the data revealed that by increasing the effective confining pressure, the liquefaction resistance decreases. A limited number of tests in a same fine content, but different plasticities showed that with increasing the plasticity of fines, the liquefaction resistance increases. Finally, a series of SEM pictures were prepared and the interaction of sand grains and clay particles was studied. The SEM pictures showed that the test results were in good consistence with the observed mechanical interaction of sand and clay.

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