Undrained behavior and post-liquefaction behavior of sand containing fines

Alberto Yolanda

i) Department of Civil Engineering, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo, 113-8656, Japan

ABSTRACT

The influence of fines on undrained behavior of sand was evaluated through a series of tests conducted in silty sand retrieved from Tokyo Bay after the 2011 Tohoku Earthquake and an artificial mix of low-plasticity fines with sand. Since the use of density measures as void ratio, relative density or sand skeleton void ratio has led to divergent results, a different approach was taken in this research, by using compaction energy as the parameter of comparison. Stress-strain curves and stress paths for non-plastic and low-plastic fines are given. Excess pore pressure development and liquefaction curves are provided and compared. It can be seen that the addition of fines decreases liquefaction resistance either if they are of non-plastic or low-plastic nature. After conducting cyclic shearing, drainage was opened to measure volumetric deformation and results are also reported. Relevant conclusions regarding the role of fines in liquefaction potential and post-liquefaction behavior are provided.

Keywords: fines content, low-plastic fines, liquefaction resistance, cyclic response, post-liquefaction deformation

1 INTRODUCTION

The undrained behavior of sand containing fines has been studied by different approaches both in the field and laboratory; nevertheless, there are no conclusive results.

For instance, the studies carried out in field by Seed et al. (1984), Robertson & Campanella (1985) or Pehlivan et al. (1999) provided some insight into the behavior of silty sand, always exhibiting higher resistance to liquefaction than clean sand. On the other hand, other researchers have embraced laboratory testing to identify the influence of fines in the liquefaction potential of sand (e.g., Shen et al. 1977; Kuerbis et al. 1988; Lade & Yamamuro 1997; Thevanyagam 1998; Polito & Martin 2001). Outcomes from these researches are often contradictory and the actual effects cannot be entirely understood. The use of a certain parameter of comparison has led to most of these misperceptions.

For example, if the void ratio is kept constant in tests, liquefaction resistance decreases as fines content increases (Thevanyagam 1998; Huang et al. 2004), until a certain point where the behavior is reversed. If relative density is kept constant, liquefaction resistance exhibits an increase with fines, again until a threshold where there is an opposite response (Kuerbis et al. 1988; Polito & Martin 2001).

Such locus is illustrated in Figure 1 and called the threshold fines content, where the amount of fines completely fills the voids in the sand matrix causing the largest decrease in void ratio and after which, fines begin to have contact with the sand grains.

As more fines are added, they start controlling the behavior and, as show in Figure 1, both maximum and minimum void ratios start increasing again reaching higher values than clean sand. The void range, ε_{max}−ε_{min}, might decrease or increase depending on the ratio of mean diameters of sand and silt, D_{50}/d_{50}. If void range decreases, as it does in most cases (e.g., Shen et al. 1977; Carraro et al. 2003), arrange of particles will provide higher resistance.

Hence, when researchers choose relative density as the parameter of comparison for FC<FC_{th}, cyclic resistance ratio increases with fines. On the other hand, keeping void ratio constant causes a decrease in relative density with the consequent reduction of liquefaction resistance with fines up to FC_{th}. Considering the experiments by Panayiotopoulos (1989) for packing of sands, the minimum and maximum void ratios corresponding to states of dense and loose random packing are the most meaningful measures of packing behavior.

Nevertheless this void range is less significant after reaching the threshold fines content or the limiting fines content, F_{lim}, the value where fines start controlling the behavior of the whole mixture (Thevanyagam 2000). Given that the use of density measurements does not allow for a complete understanding of the soil in its natural state, compaction energy was used as the parameter of comparison in this paper to reproduce to some extent the behavior that silty soil would have in the field.
2 EXPERIMENTAL PROCEDURE

Two different sands were used for the experimental program: sand ejecta from Tokyo Bay after the 2011 Tohoku Earthquake which naturally has non-plastic silt, hereinafter called TBS; and a mixture of this sand with low-plasticity fines, called LPTBS. All samples were prepared through air pluviation with a constant height of fall to use compaction energy as the parameter of comparison.

Fig. 2. Stress-strain curves and stress paths for TBS and LPTBS for FC=10% and CSR=0.20 for a) TBS AP-50 cm stress-strain and b) stress path; c) TBS AP-5 cm stress-strain and d) stress path; and e) LPTBS AP-5 cm stress-strain and f) stress path.
TBS was prepared with 5 and 50 cm of height of fall and fines content was varied from 0 to 80%. LPTBS contained fines with a plasticity index of 9 (liquid limit, LL=40.6% and plastic limit, PL=31.4%), below PI=12 the limit established by Bray & Sancio (2006) to define a soil as potentially liquefiable. The LPTBS samples were formed keeping a height of fall of 5 cm with 10% (LL= 27.9, PL=26.8), 20% (LL=27.1, PL=26.4) and 30% (LL=26.9, PL=26.6).

A hollow cylindrical torsional shear device was used. The device subjects a thin hollow cylindrical specimen (190 mm height, 60 mm internal diameter and 100 mm external diameter) to a combination of axial and torsional stresses. After reconstitution, saturation was conducted with the double vacuum method until achieving Skempton’s parameter B≥0.96. Once fully saturated, samples were isotropically consolidated to an effective confining pressure of 100 kPa.

3 CYCLIC LOADING

Typical curves of stress-strain behavior and effective stress paths are shown in Figure 2, for both TBS and LPTBS, at the same cyclic stress ratio, CSR=0.20 and fines content, FC=10%. Liquefaction was defined as 5% double amplitude shear strain. TBS sample prepared at 50 cm of height of fall (AP-50 cm) shows higher resistance and more significant degradation of shear modulus than the one prepared at 5 cm (AP-5 cm). The LPTBS sample of AP-5 cm has even less resistance than the TBS at the same height of fall; it reaches initial liquefaction (excess pore pressure equal to 0) after 3 cycles and also shows larger shear strain.

3.1 Non-plastic fines and low-plastic fines

Excess pore pressure development for AP-5 cm is shown in Figure 3. On the left side, it is observed that for non-plastic fines (TBS), pore pressure ratio, ru, increases faster for 60% fines content, while the lowest increase is for 0%. From 0 to 20%, excess pore pressure generation is more rapid, while the curve for 30% is slower and very similar to the one of clean sand.

In the case of low plasticity (LPTBS), the samples of 10, 20 and 30% fines content are very similar among each other, although they exhibit faster development of excess pore pressure than clean sand and sand with non-plastic fines.

Liquefaction curves for both TBS and LPTBS are presented in Figure 4. It is clear that clean sand has greater liquefaction resistance and that the resistance decreases with the addition of fines. However three different kinds of behavior are identified in the group of non-plastic fines. From 0 to 20% there is a decrease in resistance. Then, from 20 to 40% there is a relative rise in liquefaction resistance. Lastly, a moderate reduction is observed in the following samples. The cyclic resistance ratio, CRR20, of the sample with 60% of fines has a decrease of 25% with respect to the sample with 40% of fines. Nevertheless, there is a rise in the CRR20 as fines reach 80%.

In the case of fines with low plasticity in Figure 4, a consistent reduction is observed as fines content increases. In this case, the sample of 30% of fines does not show a higher resistance than that of 20%. In overall, the liquefaction resistance of samples with low plasticity is lower than those with non-plastic fines, which indicates that small amounts of plasticity do not necessarily improve the liquefaction resistance of sand. As the samples for AP-5 cm are being compared, it can be pointed out that the effect of soil gradation and the amount of fines might be more significant than that of plasticity.
3.2 Comparison of samples made through AP-5 cm and AP-50 cm

Figure 5 presents the liquefaction curves of TBS for AP-50 cm and the comparison of CRR20 between AP-5 cm and AP-50 cm. The set of curves on the left side display a similar response to the one described in the previous section for TBS, though there is a difference in the ranges of fines content. From 0 to 30% there is a drop in CRR20, while there is a slight raise in resistance from 40 to 50%. From 60 to 80%, there is a small decrease in liquefaction potential. In the right side it can be observed that resistance is higher for AP-50 cm compared to AP-5 cm, as expected due to the increase in density. However, the difference in CRR20 is almost negligible for the larger fines contents. Another difference is observed in the peak values of CRR20. While for AP-5 cm the highest value is around 40%, for AP-50 cm the top is around 50%. A slightly increase is observed for 30, 60 and 80% in the AP-50 cm set.

From a practical point of view it is important to know how fines content affects the SPT-N value, in this regard the coefficient of volume compressibility, mv, can be acceptable as a mechanical property of soil which is related to SPT-N value. Figure 6 shows the variation of mv with CRR20. Three different groups of behavior can be observed, the one dominated by the sand (0-20%) where CRR20 decreases and mv increases, the intermediate group (30 to 50%) where CRR20 increases as mv decreases, and the dominated by fines (60-80%), where the largest values of mv are found and CRR20 slightly grows for the largest fines content.

4 POSTLIQUEFACTION BEHAVIOR

After applying cyclic shear and reaching a shear strain of about 9% for the TBS samples prepared with AP-5 cm, drainage was opened and samples were allowed to deform while volumetric strain was measured. Figure 7 shows the evolution of volumetric strain with time for CSR=0.15. It is observed that samples with 20, 60 and 30% of fines exhibited larger volumetric strain, while the samples with 0 and 10% had the lowest values. In overall, it can be seen that sand containing fines can have larger deformation after shearing. These results resemble those introduced by Torrihara et al. (2000) where post-liquefaction volumetric strain was measured on silty soil and the compilation presented by Ishihara et al. (2004) where factor of safety is related to post-liquefaction volumetric strain and it is observed that silty sand exhibited larger volumetric strain than clean sand at similar relative densities.
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