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Cyclic Strength of Clay-Like Materials

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ABSTRACT

Failures originating in clay layers after recent earthquakes have shown the needed to study the cyclic behavior of clay-like materials. Laboratory prepared soil samples composed of kaolinite, montmorillonite and quartz were tested in a cyclic simple shear device. The results were used to develop cyclic strength curves representing 2.5%, 5% and 10% double amplitude shear strains. Using these curves, the effect of plasticity characteristics and mineralogical composition on the cyclic resistance was evaluated. The results showed as the plasticity increased the cyclic resistance of the soils increased. The cyclic resistance of montmorillonite-quartz mixtures was slightly higher cyclic resistances than that in kaolinite-quartz mixtures with the same plasticity index.

Introduction

The Anchorage Landslide following the 1964 Alaska Earthquake (Stark and Contreras, 1998; Boulanger and Idriss, 2004), damage to the Moss Landing Marine Laboratory after the 1989 Loma Prieta (Boulanger et al., 1998), and the severely damaged buildings found on clays after the 1985 Mexico Earthquake (Mendoza and Auvinet, 1985) have all emphasized the need for detailed study regarding the cyclic behavior of clay-like materials. Clay-like materials are defined by MSHA (2009) as those soils that exhibit behavior similar to that typically exhibited of clays. Although the literature contains results showing the effect of plasticity on the cyclic behavior of clay-like materials, the results presented from the different researchers are inconsistent. Moreover, very little information is presented in the literature regarding the influence of the mineralogical composition on the cyclic resistance.

Based on the results from cyclic simple shear and cyclic triaxial tests on undisturbed samples from Turkey, Bray and Sancio (2006) and Bray et al. (2004) developed cyclic strength curves, or plots showing the number of cycles along the horizontal axis in logarithmic scale and the cyclic stress ratio on the vertical axis for their soils. They found that these curves could not be developed for soils with plasticity indices greater than 18 and that two cyclic strength curves could be used to represent the cyclic behavior of soils with plasticity indices less than 18. The first curve is for soils with plasticity indices less than 12, whereas the second is those soils with plasticity indices greater than 12, but lower than 18. Soils with plasticity indices between 12 and

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18 are noted to have greater cyclic resistances than the soils with plasticity indices less than 12. However, Guo and Prakash (1999) and El Hosri et al. (1984) found that the cyclic resistance first decreases as the plasticity index is increased to a value of 5 and then, increases in soils with increasing plasticity indices beyond 5. When the plasticity index was increased from 2 to 4, Sandoval (1989) and Prakash and Sandoval (1992) showed that the cyclic resistance decreases.

Very few studies have examined the effect of clay mineralogy on the cyclic behavior of clay-like materials. In a study by Beroya et al. (2009), the cyclic behavior of mixtures of silts with clays was found to be substantially affected by the dominate clay mineral. They concluded that although the plasticity of the soil influences the cyclic behavior, the plasticity index does not serve as a strong indicator of the influence of clay mineralogy. Kuwano et al. (1996) also noted that mineralogy must be considered in order to thoroughly understand the cyclic behavior of clays. Both of these studies noted that effect of clay mineralogy is still not clearly understood and that further study is needed. In this study, laboratory prepared soils are used to methodically understand the influence of clay mineralogy and plasticity characteristics on the cyclic behavior of clay-like materials.

Methodology

Commercially purchased montmorillonite, kaolinite and quartz were used to prepare 10 mixtures of kaolinite with quartz and 4 mixtures of montmorillonite with quartz. For each mixture of kaolinite or montmorillonite with quartz (herein referred to as kaolinite-quartz mixtures and montmorillonite-quartz mixtures, respectively), the Atterberg limits were measured following the procedure outlined in ASTM D 4318. Figure 1 shows the plasticity characteristics for all of the samples tested in this study in a plasticity chart. The numbers next to the points shown in Figure 1 represent the sample numbers.

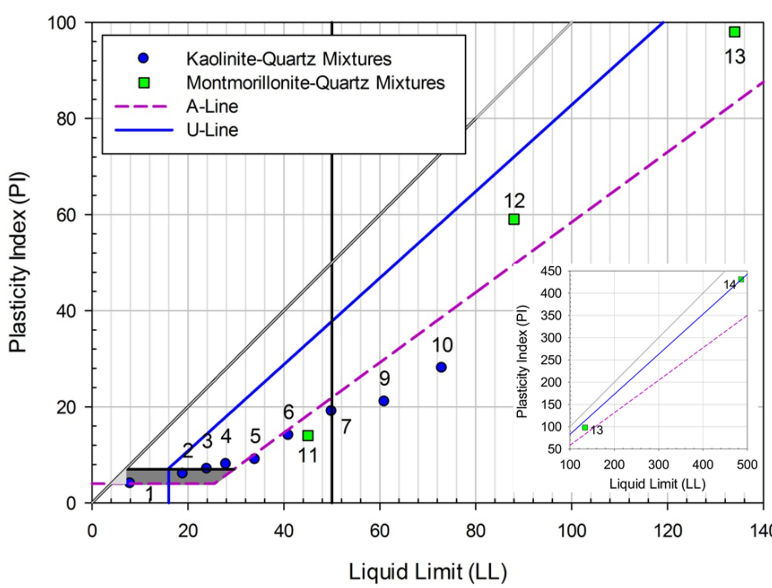


Figure 1. Plasticity chart showing liquid limit and plasticity index for the samples tested

Samples were prepared by mixing dry powdered minerals at the desired compositions at an initial moisture content equal to the measured liquid limit. The samples were allowed to hydrate for at least twenty-hours before the sample was placed in a membrane and confined by a stack of Teflon coated rings in a cyclic simple shear apparatus. An NGI-type cyclic simple shear device was used to conduct the cyclic testing in this study since the simple shear can better model the stresses experienced in the soil as a result of ground shaking (Seed and Peacock, 1971; Song et al., 2004). The sample was first consolidated to a pressure of 25 kPa. After the completion of the primary consolidation, the stress was increased to 50 kPa and later, to 100 kPa, which was the final consolidation pressure for the samples tested. Figure 2 shows the cumulative axial strain as a function of time in logarithmic scale for each of the three consolidation steps. The relationship between the void ratio and the vertical consolidation pressure in logarithmic scale (e-log σ_c' plot) is also presented in Figure 2. For comparison, the e-log σ_c' plot obtained by Tiwari and Ajmera (2011) for the same sample at the same initial moisture content tested in a consolidometer is also included. As seen, the consolidation results are similar regardless of device (cyclic simple shear or consolidometer) used. Although not presented in this paper due to space limitations, the behavior observed in the remaining samples was similar to that presented here.

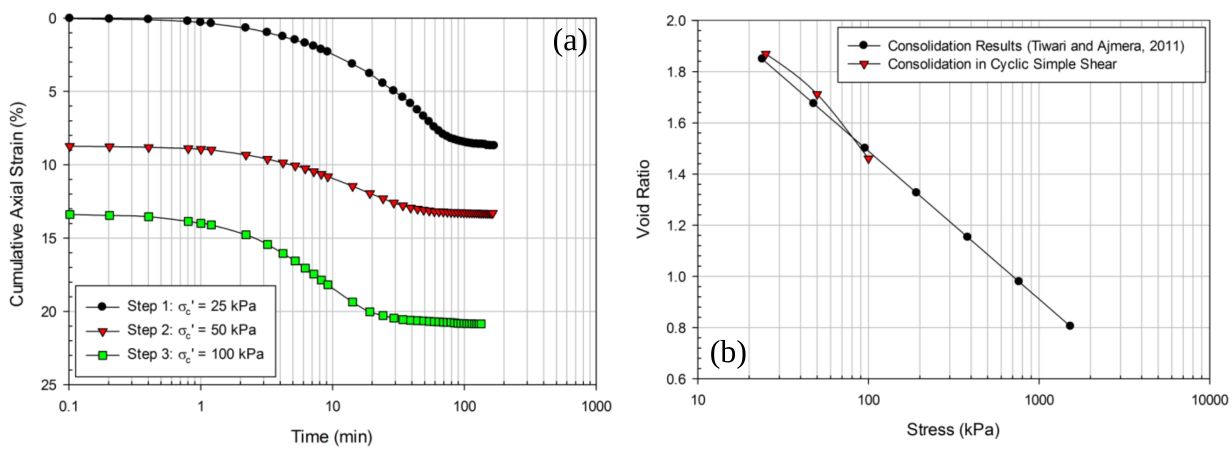


Figure 2. Results from Sample No. 7 showing (a) cumulative axial strain as a function of time in logarithmic scale and (b) e-log σ_c' plot for consolidation in consolidometer and cyclic simple shear devices

After the completion of the primary consolidation at 100 kPa, constant volume, stress-controlled cyclic loading in the form of a 0.5 Hz frequency sinusoidal wave was applied. The amplitude of the cyclic loading was determined by the cyclic stress ratio (CSR) or the ratio of the amplitude of the applied cyclic stress to the vertical consolidation pressure. The cyclic loading characteristics are shown schematically in Figure 3, which shows the applied cyclic loading function, the resulting pore pressure and effective vertical pressure. The hysteresis loop resulting as a result of the fifth cycle of loading is also presented in Figure 3. Typical hysteretic behavior for Sample No. 7 at a cyclic stress ratio of 0.16 is shown for several selected samples in Figure 4. Similar behavior was also seen at the different cyclic stress ratios for this sample and also for all of the samples tested in this study. It should be noted that at some high strain levels, some of the hysteresis loops appeared "banana"-shaped.

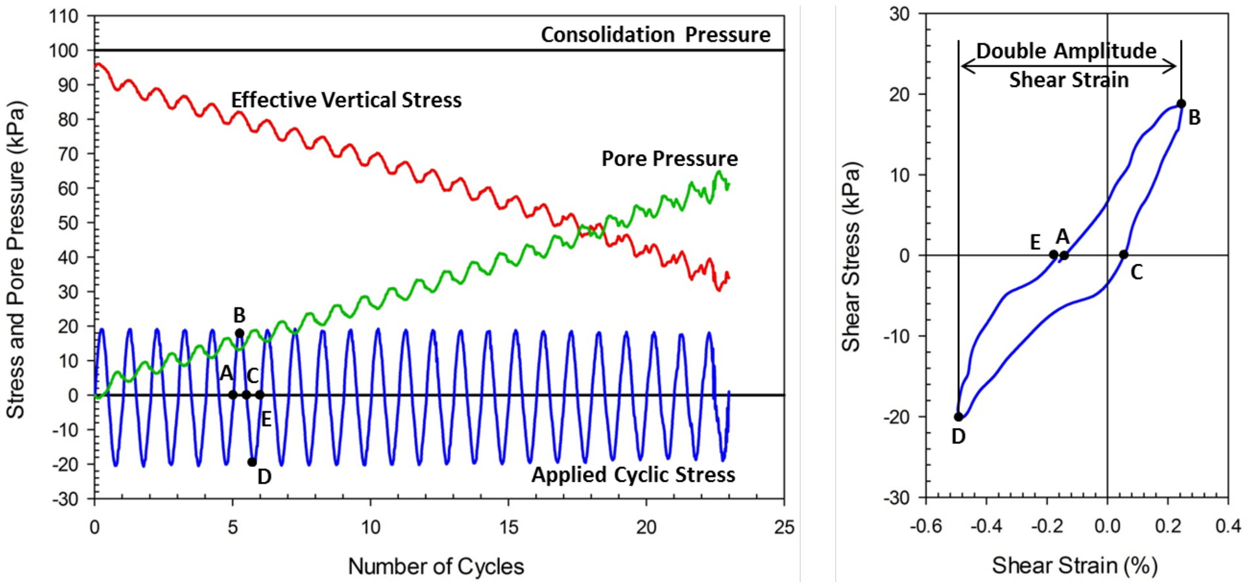


Figure 3. Schematic of applied cyclic stress, resulting pore pressure and effective vertical stress along with sample hysteresis loop showing calculation of double amplitude shear strain

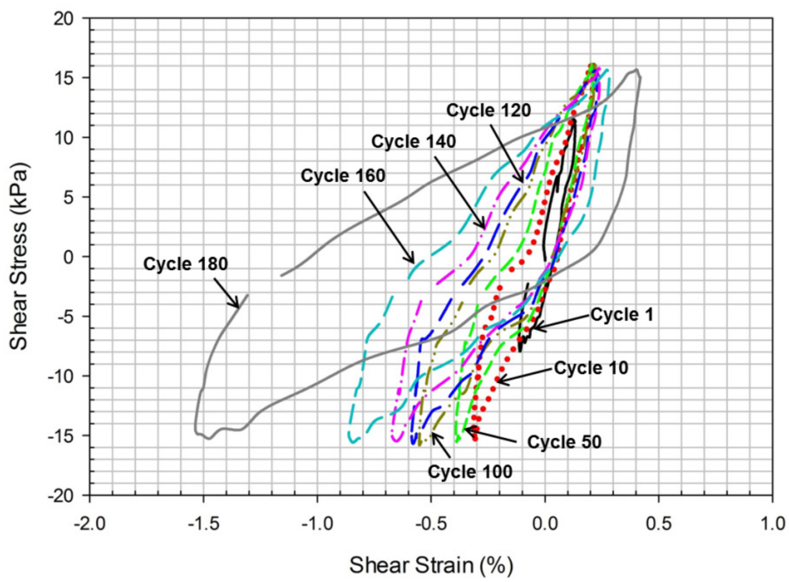
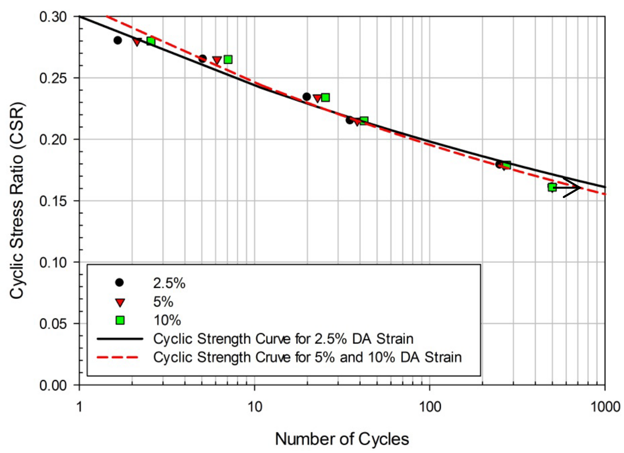


Figure 4. Example stress-strain hysteresis loops for selected cycles of loading; Results from Sample No. 7 at a cyclic stress ratio of 0.16 are presented

At the end of each cycle, the double amplitude shear strain resulting from cyclic loads was calculated as shown in Figure 3. The sample was subjected to cyclic loading until it experienced 10% double amplitude shear strains. If the sample did not reach this strain in 500 cycles, the cyclic phase of the test was terminated.

Results

The computed double amplitude shear strains at the end of each cycle were interpolated to calculate the number of cycles to the nearest tenth of a cycle required to cause 2.5%, 5% and 10% double amplitude shear strain. The results were used to develop cyclic strength curves representing the cyclic resistance provided by the material at the strain levels of 2.5%, 5% and 10%. Figure 5 shows the typical behavior observed in the cyclic strength curves for kaolinite-quartz mixtures and for montmorillonite-quartz mixtures. Points with the rightward pointing arrow represent those tests in which cyclic loading was terminated at 500 cycles since 10% double amplitude shear strains were not achieved prior to this cycle of load. It is seen from Figure 5 that a small number of additional cycles of loading are required to cause 10% double amplitude shear strain in kaolinite-quartz mixtures after the sample has experienced 2% double amplitude shear strains. However, in montmorillonite-quartz mixtures, a more substantial number of cycles are required to cause 10% double amplitude shear strains after 2% double amplitude shear strains are achieved.



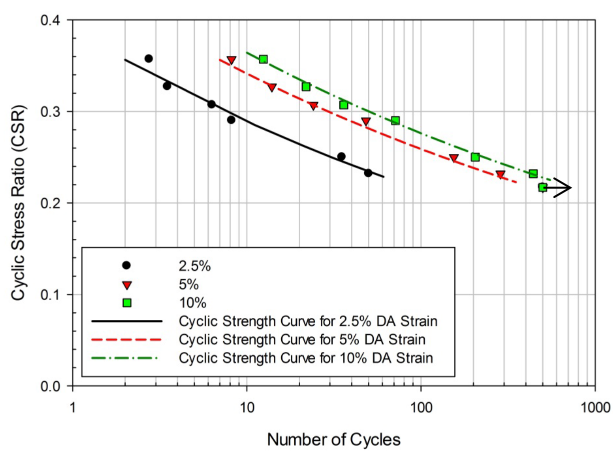


Figure 5. Cyclic strength curves for 2.5%, 5% and 10% double amplitude shear strains for (a) kaolinite-quartz mixture (Sample No. 7) and (b) montmorillonite-quartz mixture (Sample No. 12)

Figure 6 shows the cyclic strength curves at 5% double amplitude shear strains for five selected samples with varying plasticity indices and mineralogical compositions. The remaining samples are not shown in this figure, in order to clearly seen the effect of both mineralogy and plasticity on the cyclic behavior. As it can be seen from Figure 6, the cyclic strength curves showed increasing cyclic resistance with increasing plasticity index. Some researchers, including Bray and Sancio (2006), Guo and Prakash (1999) and Gratchev et al. (2006), have stipulated that the plasticity index is the key to understanding the cyclic behavior of clays. Other studies, such as Beroya et al. (2009) and Kuwano et al. (1996) have noted that the plasticity index is not a strong indicator of the mineralogy of clays, which must be considered in order to thoroughly understand the cyclic behavior. By examining the cyclic strength curves, shown in Figure 6, for two soils with the same plasticity index and similar void ratios prior to cyclic loading, but different mineral compositions, it is clear that clay mineralogy substantially affects the cyclic behavior of clay-like materials. Furthermore, as the plasticity index is the same in both samples, it is evident that the cyclic behavior cannot be solely evaluated from the plasticity index.

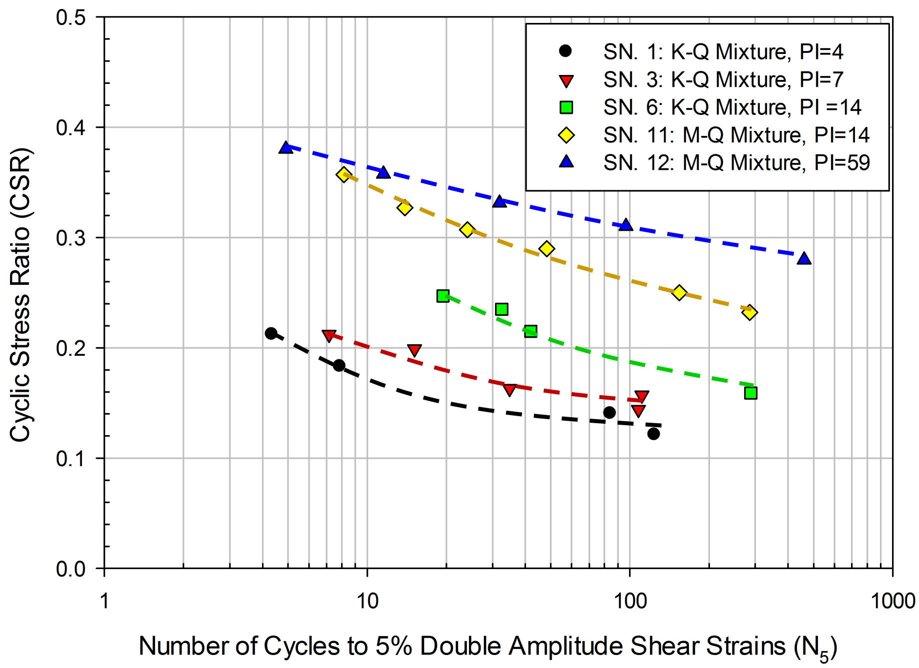


Figure 6. Cyclic strength curves for several selected samples; Two samples (Sample No. 6 and Sample No. 11) with the same plasticity indices (14) and similar void ratio ratios (1.33 and 1.32, respectively) after consolidation, but different mineralogical compositions

Conclusions

As a result of recent failures in clay layers following an earthquake and the lack of consistent results in the literature, 14 soils samples were prepared in the laboratory to evaluate the effect of plasticity and clay mineralogy on the cyclic behavior of clay-like materials. The study concludes:

- As the plasticity index increased, the cyclic resistance was found to increase via visual examination of the cyclic strength curves.
- Moreover, by examining two soils with the same plasticity index and similar void ratios after consolidation and just prior to cyclic loading, but different mineralogical compositions, substantial differences in the cyclic resistance are noted.
- Plasticity index alone does not incorporate the effects of clay mineralogy, contrary to the results of many published articles. Clay mineralogy must be considered in order to completely understand the cyclic behavior of clay-like materials.

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