

Undrained Cyclic Behavior of Mixtures of High-Plasticity Clay and Sand

Ivan Borisovich GRATCHEV*, Kyoji SASSA and Hiroshi FUKUOKA

* Graduate School of Technology, University of Tokyo

Synopsis

The cyclic behavior of mixtures of high-plasticity clay (commercial bentonite) and sand and factors affecting it were studied by means of a ring-shear apparatus. It was found that bentonite content had a significant influence on the liquefaction process of the studied soils. A small amount of bentonite in the mixtures (<7%) would cause the formation of "loose" microstructures, resulting in the occurrence of rapid liquefaction under cyclic loading, while a high bentonite content (>11%) would cause the formation of clay matrixes, thus raising the soil's resistance to liquefaction. In addition, the effect of pore water chemistry on the cyclic behavior of a high plasticity bentonite-sand mixture was carefully examined. It was found that the presence of ions in pore water changed the soil's microstructure, making it more vulnerable to liquefaction. The results from a series of undrained cyclic shear displacement-controlled tests revealed the strong influence of loading frequency on the cyclic behavior.

Keywords: liquefaction, bentonite, pore water chemistry, loading frequency

1. Introduction

Prediction of natural disasters that involve earthquake-induced liquefaction of fine-grained soils is a formidable challenge due to the great number of factors that need to be carefully considered in making such a prognosis. However, the liquefaction of clayey soils have been relatively poorly studied compared with those of clean sand and silt due to the assumption that clayey soils do not liquefy. There has been much evidence indicating the occurrence of liquefaction in sand containing clay particles. Youd et al. (1989) reported the liquefaction of silty sands with as much as 10% clay that occurred at the Kornbloom site in the Imperial Valley, USA, during the 1981 Imperial Valley earthquake. Miura et al. (1995) noted liquefaction of soils with up to 48% fines and 18% clay fraction due to the 1993 Hokkaido Nansai-Oki earthquake. Liquefaction of fine-grained soils during earthquake has also been observed in China (Perlea et al. 1999) and Tajikistan (Ishihara et al. 1990). More recently,

Sassa (2005) and Gratchev et al. (2005) reported the liquefaction of silty sand with up to 12% clay near Niigata city, Japan, during the 2004 Mid-Niigata Prefecture earthquake.

The above examples pose many questions, of which the most important are: 1) where to draw a boundary between the liquefiable and non-liquefiable soils; and 2) what criteria to use for estimating the liquefaction potential of clayey soil. In order to address these questions, the mechanism of the cyclic behavior of clayey soils as well as the factors affecting it need to be studied. This paper presents the results of an investigation on this issue. The research was conducted on artificial mixtures of silica sand with bentonite by means of a ring-shear apparatus. The obtained results revealed the strong influence of bentonite content, pore water chemistry and loading frequency on the cyclic behavior of bentonite-sand mixtures.

2. Background

Most of studies on the liquefaction of clayey sand conducted in recent years have focused on the effects of clay mineralogy (particularly low plasticity kaolin) and soil plasticity. Georgiannou et al. (1991) investigated the cyclic behavior of kaolin-sand mixtures and concluded that progressive addition of the clay promoted the formation of loose structures as the clay particles reduced the number of contact points between the sand grains, ultimately increasing the liquefaction potential of clayey sand. Gratchev et al. (2004a) studied the influence of clay mineralogy on the cyclic behavior of artificial clay-sand mixtures. It was found that bentonite-sand mixtures were more resistant to liquefaction than kaolin- and illite-sand mixtures, given the same clay content.

A fair amount of research has been conducted to investigate the influence of soil plasticity on the cyclic behavior of clayey soil (Prakash & Sandoval, 1992; Ishihara, 1993; Hyodo et al., 1999; Perlea et al., 1999). More recently, Gratchev et al. (2005, 2006) showed that for artificial clay-sand mixtures, as well as for natural soils collected from earthquake-induced landslides, an increase in soil plasticity raised the soil resistance to liquefaction, and soils with plasticity index (PI) of more than 15 are nonliquefiable.

It can be inferred from the above review that the cyclic behavior of clayey soils, especially high-plasticity clayey soils, still remains unclear, and the factors which influence it are poorly studied. This article seeks to investigate the mechanism of liquefaction of artificial bentonite-sand mixtures and clarify the effects of bentonite content, pore water chemistry and loading frequency on their cyclic behavior.

3 Sample characteristics

The samples were formed by mixing oven-dried commercially available bentonite with oven-dried sand (S7) in various proportions, as described in detail in Gratchev et al. (2007), in order to obtain bentonite-sand mixtures with different properties and microstructures.

4. Experimental outlines

4.1. Ring shear apparatus

To study the undrained cyclic behaviour of

bentonite-sand mixtures, a ring-shear apparatus (DPRI-4) was used. The structure of the DPRI-4, the principle of shearing the sample in cyclic ring-shear tests, and the method of sample preparation have already been reported in the literature (Vankov & Sassa, 1998; Sassa et al., 2005). The sample in the ring-shear box is laterally confined between pairs of upper and lower confining rings, showing the shape of a doughnut (Fig. 1).

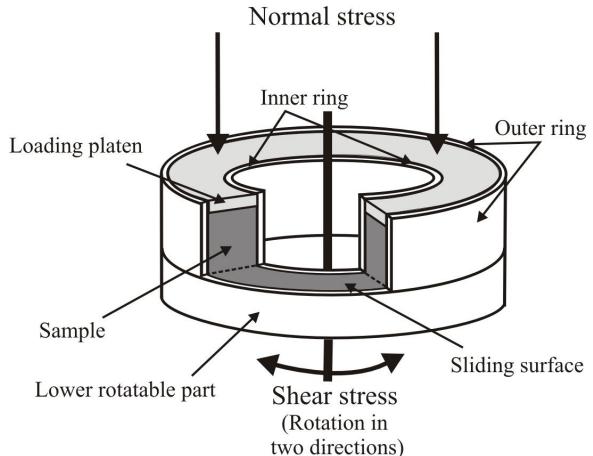


Fig. 1 The undrained cyclic ring-shear box.

4.2. Test procedure

Before each test, the sample was set into the shear box by dry deposition method and then saturated by means of carbon dioxide and de-aired water. To study the influence of pore water chemistry on the cyclic behavior of bentonite-sand mixture, samples formed from mixture of S7 with 11% bentonite were treated with solutions of sodium chloride (NaCl) and calcium carbonate (CaCO_3) in the following concentrations: 0.01 and 0.1 mol. The degree of saturation was examined by measuring the BD value, which was defined as the ratio between the increments of generated pore pressure (Δu) and normal stress ($\Delta \sigma$) ($\text{BD} = \Delta u / \Delta \sigma$) (Sassa, 1985). The ratio for each test was ensured to be more than 0.95, a value that indicated an approximately full saturation. All samples were normally consolidated under a confining stress of 105 kPa to the same void ratio of 0.82. After consolidation, three series of undrained cyclic tests were carried out to investigate the effects of (1) bentonite content, (2) pore water chemistry, and (3) loading frequency. In the first two series, a reversal shear stress (τ) with amplitude of about 45 kPa and a loading frequency (f) of 0.5 Hz were applied for 50 cycles (shear stress-controlled conditions). In the third series, a reversal shear displacement (l) of 5 mm was applied for 500 seconds with three different loading frequencies:

0.05, 0.5, and 3.0 Hz.

After each test, a cyclic stress ratio (CSR), defined as the ratio of the maximum cyclic shear resistance to the normal stress, was measured for the last cycle of loading in order to compare the obtained results for different soils. It is noted that the mixtures with CSR smaller than 0.1 and the value of pore water pressure generated higher than 95% of that of normal stress were considered to have liquefied.

5. Results and Discussion

5.1. The effect of bentonite content on the cyclic behavior of bentonite-sand mixtures

To demonstrate the significant role of bentonite content in the cyclic behavior of bentonite-sand mixtures, three examples from the first series of ring-shear tests will be briefly discussed here. Fig. 2 presents an example of the time series data of normal stress, pore water pressure, cyclic shear resistance and shear displacement obtained for the mixture of S7 with 7% bentonite (B7). In this case, the pore water pressure generated rapidly, triggering liquefaction after only 5 cycles.

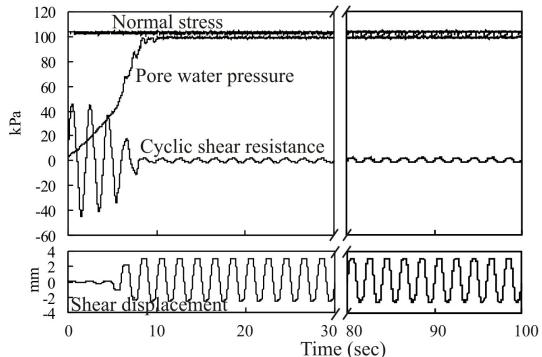


Fig. 2 Results of undrained cyclic shear stress-controlled ring-shear test on mixture of S7 with 7% bentonite (B7)

Fig. 3a plotted as the bentonite content against CSR showed that all the mixtures with bentonite content smaller than 11% liquefied ($CSR < 0.1$) and the mixtures with bentonite content higher than 11% seemed to be resistant to liquefaction. Fig. 3b plotted as the bentonite content against the number of cycles necessary for the onset of liquefaction (N) showed that the progressive addition of bentonite (from 0 to 7%) to S7 reduced N with the threshold to be at 7%, which is the percentage at which N reached its minimum value (5 cycles). However, a further increase in bentonite content raised the soil resistance to liquefaction: the mixture of S7 with 9%

bentonite (B9) liquefied after as many as 17 cycles, while B11 and B15 were observed to be resistant to liquefaction.

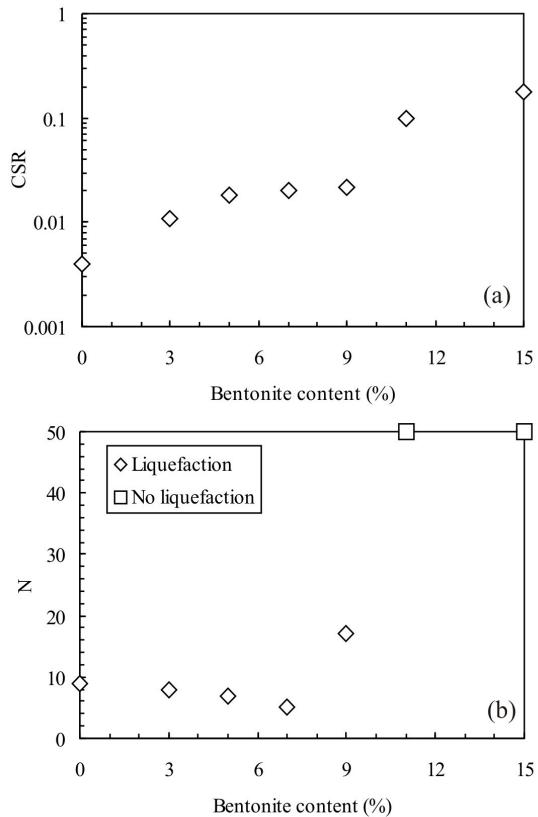


Fig. 3 Results of the first series of ring-shear tests plotted as bentonite content against CSR (a), and bentonite content against N (b)

5.2. The effect of pore water chemistry on the cyclic behavior of bentonite-sand mixtures

The strong influence of pore water chemistry on the properties of clayey soils is well documented; for this reason, this factor was assumed to be important to the cyclic behavior of bentonite-sand mixtures. To study the effect of pore water chemistry, a few samples formed from the mixture of silica sand with 11% bentonite were treated with solutions of NaCl and CaCO₃ and their cyclic behavior and microstructures carefully observed. All results from the second series of cyclic undrained ring-shear tests are presented in Fig. 4 in terms of the ions concentration against CSR. Clearly, the change in pore water chemistry caused the samples to liquefy under cyclic loading ($CSR < 0.1$). To understand why the same mixture underwent such dramatic changes in cyclic behavior, the microstructures of all the samples were

studied. The SEM analysis revealed the strong influence of the used ions on the distribution and state of clay matter. It is noted that the formation of clay aggregates is usually accompanied by a decrease in plasticity (Rosenqvist, 1959; Mesri&Olson, 1971), a phenomenon that was indeed observed. Decidedly, pore water chemistry has a great effect on the cyclic properties of bentonite-sand mixtures and needs to be further studied.

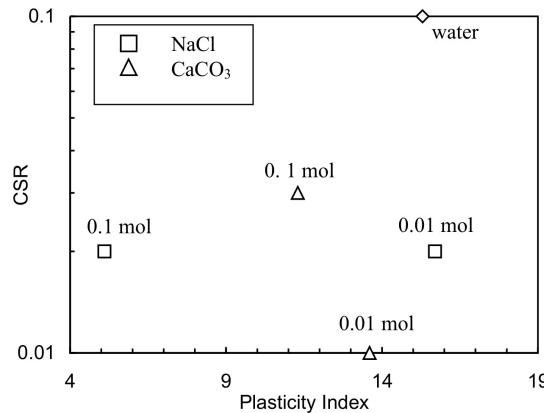


Fig. 4 Results of the second series of ring-shear tests plotted as plasticity index against CSR

5.3. The effect of loading frequency on the cyclic behavior of bentonite-sand mixtures

The influence of loading frequency on the cyclic behavior of soil seems to be well-understood but only for stress-controlled conditions. For clayey soils as well as sandy soils, lower loading frequencies produce greater strain or shear displacement, resulting in a greater loss of strength (Kramer et al., 1992; Gratchev et al., 2004b; Sassa et al., 2005). However, the influence of loading frequency on the cyclic behavior of clayey soil under shear displacement-controlled conditions still remains unclear. To study it, a third series of undrained cyclic tests were conducted. The samples formed from the mixture of S7 with 11% bentonite were subjected to cyclic loading with a reversal shear displacement of 5 mm and three loading frequencies: 0.05, 0.5 and 3 Hz. The purpose of this series of experiments was to compare the values of generated pore water pressure and cyclic shear resistance obtained for different loading frequencies but after the same period of time (500 sec). The obtained results showed that the used period of loading was sufficient for each sample to reach a steady state.

Fig. 5 summarizes the results obtained in the third series of ring-shear tests plotted as loading frequency against

CSR and r_u (r_u - excess pore water pressure ratio defined as the ratio of pore water pressure generated to normal stress) measured after 500 seconds. As can be seen, the influence of loading frequency on the cyclic behavior of the studied mixture in shear displacement-controlled ring-shear tests is remarkable; that is, an increase in loading frequency (from 0.05 to 3 Hz) led to a higher value of r_u and a smaller value of CSR. A similar finding was obtained by Seed & Chan (1957), who investigated the cyclic behavior of clayey soil by means of triaxial tests. In that work, the greater loss of cyclic shear strength under a higher loading frequency was attributed to the thixotropic nature of the studied soil. Thixotropy, a process of bond restoration resulting in some strength recovery, has been well-studied (Mitchell, 1960; Osipov et al., 1984; Barnes, 1997). It was found that the thixotropic recovery was time-consuming and increased when the time interval between loading cycles also increased. Therefore, the loss of cyclic strength under lower loading frequencies should be smaller than that under higher loading frequencies; and indeed it was observed during testing (Fig. 5).

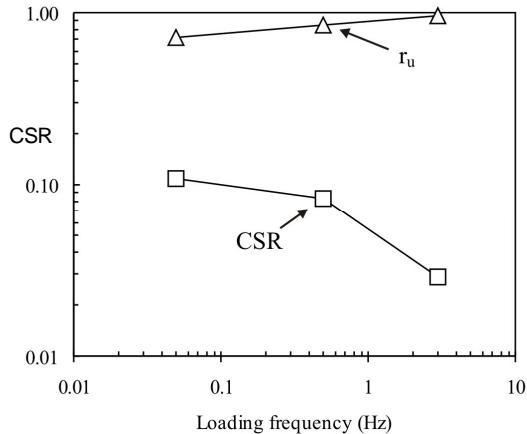


Fig. 5 Results of the third series of ring-shear tests plotted as loading frequency against CSR and r_u

6. Conclusions

The undrained cyclic behavior of bentonite-sand mixtures was studied by means of a ring-shear apparatus. The following conclusions could be drawn:

1. Bentonite in small percentages (until 7%) decreased the sand resistance to liquefy because the clay matter formed "clay bridges" between sand grains that were easily destroyed during cyclic loading. However, further increase in the bentonite content raised the soil

resistance to liquefaction, a phenomenon that was attributed to the formation of a clay matrix.

2. Pore water chemistry had a strong influence on the liquefaction potential of clayey soil. The presence of ions in pore water changed the microstructure of the studied mixture, making it more vulnerable to liquefaction

3. Increase in loading frequency decreased the resistance of bentonite-sand mixture to liquefaction in shear displacement-controlled ring-shear tests.

Acknowledgements

The authors wish to thank Dr. V. Sokolov, Professor of Moscow State University, for his invaluable help with SEM analysis. This study is a part of ICL (International Consortium on Landslides) Project M124—"The influence of clay mineralogy and ground water chemistry on the mechanism of landslides" conducted jointly by the Institute of Geoscience of the Russian Academy of Science, Russia, and Kyoto University, Japan

References

- Barnes, H. (1997): Thixotropy-a review, Non-Newtonian Fluid Mech, 70, pp.1-33.
- Georgiannou, V.N., Hight, D.W. and Burland, J.B. (1991) :Undrained behaviour of natural and model clayey sands, Soils and Foundations; Vol.31, No.3, pp.17-29.
- Gratchev, I.B., Sassa, K. and Fukuoka, H. (2003): Effect of salt concentration and pH of pore water on liquefaction on clayey sands under dynamic loading in a ring shear apparatus, in Proceedings of the Forty Second Annual Conference of Japan Landslide Society, Toyama, pp. 285-288.
- Gratchev, I.B., Sassa, K. and Fukuoka, H. (2004a): Cyclic behavior of clayey sands under different physico-chemical conditions, in: Lacerda, W., Ehrlich, M., Fontoura, S., and Sayao, A. (eds.) Proceedings 9th International Symposium on Landslides, Rio de Janeiro, Brazil, Balkema, Vol. 1, pp. 701-704.
- Gratchev, I.B., Sassa, K. and Fukuoka, H. (2004b): Influence of loading frequency on the liquefaction of clayey sands, in Proceedings of the Forty Third Annual Conference of Japan Landslide Society, Akita, pp. 131-134.
- Gratchev, I.B., Sassa, K. and Fukuoka, H. (2005): Analysis of earthquake-induced landslides in soils with different clay content in Japan, in Proceedings of the International Symposium on Latest Natural Disasters-New Challenges for Engineering Geology, Geotechnics and Civil Protection, Sofia, Bulgaria, on CD.
- Gratchev, I.B., Sassa, K. and Fukuoka, H. (2006): How reliable is the plasticity index for estimating the liquefaction potential of clayey sands?, Journal of Geotechnical and Geoenvironmental Engineering, ASCE, (in press)
- Gratchev, I., Sassa, K., Osipov, V.I., Fukuoka, H., and Wang, G. (2007): Undrained cyclic behavior of bentonite-sand mixtures and factors affecting it. Geotech. Geol. Eng., DOI 10.1007/s10706-006-9115-2.
- Hyodo, M., Hyde Adrian, F., Yamamoto, Y. and Fujii, T. (1999): Cyclic shear strength of undisturbed and remolded marine clays, Soils and Foundations, Vol.39, No.2, pp.45-58.
- Ishihara, K., Okusa, S., Oyagi, N. and Ischuk, A. (1990) :Liquefaction induced flow slide in the collapsible loess deposit in Soviet Tadjik. Soils and Foundations, Vol.30, No.4, pp.73-89.
- Ishihara, K. (1993): Liquefaction and flow failure during earthquakes, Geotechnique, Vol.43, No.3, pp.351-415.
- Kramer, S., von Laun, F. and Sivaneswaran, N. (1992) :Strain-controlled, variable frequency cyclic loading system for soft soils, Geotechnical Testing Journal, Vol.15, No.3, pp.264-270.
- Mesri, G. and Olson, R. Consolidation characteristics of montmorillonite, Geotechnique, Vol.21, No.4, pp.341-352.
- Mitchell, J.K. (1960): Fundamental aspects of thixotropy in soils, Journal of the soil mechanics and foundations division, ASCE, Vol.86, No. SM 3, pp.19-52.
- Miura, S., Kawamura, S. and Yagi, K. (1995): Liquefaction damage of sandy and volcanic grounds in the 1993 Hokkaido Nansei-Oki earthquake, in Proceedings of the third International Conference on Recent Advances in Geotechnical Earthq. Engg. and Soil Dynamics, St. Louis, MO, 1, pp. 193-196.
- Osipov, V.I. and Sokolov, V.N. (1978): Microstructure of recent clay sediments examined by scanning electron microscopy, in Whalley, W.B. (eds.) Scanning Electron Microscopy in the Study of Sediments, Geo Abstracts, Norwich, England, pp. 29-40.
- Osipov, V.I., Nilolaeva, S.K. and Sokolov, V.N. (1984): Microstructural changes associated with thixotropic

- phenomena in clay soils, Geotechnique, Vol.34, No.2, pp.293-303.
- Osipov, V., Gratchev, I.B. and Sassa, K. (2005): The mechanism of liquefaction of clayey soils. in Proceedings of the First General Assembly of the International Consortium on Landslides, Washington D.C., pp. 127-131.
- Perlea, V.G., Koeste,r J.P. and Prakash, S. (1999): How liquefiable are cohesive soils. In: Seco e Pinto, P. in (eds.) Proceedings of Earthquake Geotechnical Engineering, Lisboa. Balkema, Vol. 2, pp. 611-618.
- Prakash, S. and Sandoval, J.A. (1992): Liquefaction of low plasticity silts, Soil Dynamics and Earthquake Engineering, Vol.11, pp.373-379.
- Rosenqvist, I. (1959): Physico-chemical properties of soils: soil-water systems, Journal of Soil Mechanics and Foundation Division ASCE, Vol.85, No. SM 2, pp.31-53.
- Sassa, K. (1985): The mechanism of debris flows, in Proceedings 11th International Conference on Soil Mech and Foundation Engineering, San Francisco, pp. 1173-1176.
- Sassa, K., Fukuoka, H., Wang, G. and Ishikawa, N. (2004): Undrained dynamic loading ring shear apparatus and application for landslide dynamics, Landslides, Vol.1, No.1, pp.7-21.
- Sassa, K. (2005): Landslide disasters triggered by the 2004 Mid-Niigata Prefecture earthquake in Japan, Landslides, Vol.2, No.2, pp.135-142.
- Sassa, K., Wang, G., Fukuoka, H. and Vankov, D. (2005): Shear-displacement-amplitude dependent pore-pressure generation in undrained cyclic loading ring shear tests: an energy approach, Journal of Geotechnical and Geoenvironmental Engineering ASCE, Vol.131, No.6, pp.750-761.
- Seed, H.B. and Chan, C.K. (1957): Thixotropic characteristics of compacted clays, Journal of Soil Mechanics and Foundation Division ASCE, Vol.83, No.4, pp.1-35.
- Sergeyev, Y.M., Grabowska-Olszewska, B., Osipov, V.I., Sokolov, V.N. and Kolomenski, Y.N. (1980): The classification of microstructures of clay soils, Journal of Microscopy, Vol.120, No.3, pp.237-260.
- Vankov, D.A. and Sassa, K. (1998): Dynamic testing of soils by ring-shear apparatus, in Proceedings of the 8th Congress of the International Associate for Engineering Geology and the Environment, Vancouver, Vol.1, pp. 485-492.
- Youd, T.L., Holzer, T.L. and Bennett, M.J. (1989): Liquefaction lessons learned from the Imperial Valley California, Special volume for Discussion Session on Influence of Local Soils on Seismic Response, 12th ICSMFE, Rio de Janeiro.

高塑性粘土と砂の混合材料の非排水繰り返し載荷挙動

Ivan Borisovich GRATCHEV *・佐々恭二・福岡 浩

*東京大学工学研究科

要 旨

高塑性粘土（市販のベントナイト）と珪砂の混合材料の繰り返し載荷時の挙動をリングせん断試験機を用いて調べた結果、粘土含有量が液状化特性に大きく影響することがわかった。7%以下の比較的低い粘土含有量では粗な微細構造のため繰り返し載荷時に速く液状化に到達した。一方11%以上の場合液状化抵抗が増大した。間隙水の化学組成の影響については間隙水中のイオンが微細構造に影響し液状化しやすくなる傾向が得られた。せん断変位制御の非排水繰り返し載荷試験では液状化挙動の周波数依存性があることがわかった。

キーワード：液状化、ベントナイト粘土、間隙水の化学的特性、載荷周波数