On the Role of pH in the Cyclic Behavior of Fine-Grained Soils

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Abstract

This paper describes the results of an experimental investigation aimed at establishing whether pH affects the cyclic strength of artificial and natural fine-grained soils. The undrained cyclic behavior of low plasticity (liquid limit less than 30) kaolin and illite-sand mixtures, medium plasticity (liquid limit less than 50) bentonite-sand mixture, and medium plasticity natural soil recovered from the sliding zone of an earthquake-induced landslide was studied by means of a ring-shear apparatus with a view to understanding the structural changes that occurred at different pH. The data obtained for the low plasticity clay-sand mixtures indicated that changes in pH could slightly affect the soil resistance to liquefaction. For the bentonite-sand mixture of medium plasticity, the results not only revealed the strong influence of pH but they also demonstrated that in acidic and alkaline mediums the cyclic strength of soil significantly decreased. The outcome of tests on the natural soil corroborated the tendency observed for the bentonite-sand mixture, thus emphasizing the importance of pH in the cyclic behavior of medium plasticity clays. An attempt was made to understand the cause of the remarkable pH-dependent change in cyclic strength of the studied soils based on the principles of colloid chemistry.

Keywords: pH, clay, cyclic strength, liquefaction, structure change

Introduction

A number of slope failures in fine-grained soils triggered by earthquakes have drawn the attention of geotechnical engineers to the problem of cyclic behavior of such soils. As a result, the effects of several factors on the cyclic strength of fine-grained soils, such as cyclic shear stress and frequency, initial static shear stress, clay content and clay mineralogy are already relatively well-studied. In spite of the advances made in this area, there are still some aspects concerning the undrained cyclic behavior of clayey soils that need to be further studied. For example, pore fluid composition, as a factor, has been neglected, although it is already known that the presence of ions in pore water can significantly alter the properties of clays. Furthermore, it has so far been general practice to use distilled water during testing, yet the groundwater composition of natural sites is reported to be rather different, including considerable concentrations of various ions (Torrance 1979).

To shed light on this problem, a comprehensive investigation into the influence of pore fluid chemistry on the dynamic properties of clays was conducted at Kyoto University, Japan. The study was carried out by means of a ring-shear apparatus on artificial clay-sand mixtures and a natural soil collected from the sliding surfaces of an earthquake-induced landslide. This paper presents a section of that investigation dealing with the undrained cyclic response of clayey soils to changes in pH.

Tested soils

The soils used in this study were divided into two groups based on their plastic properties. The first group consisted of low plasticity artificial kaolin and illite-sand mixtures while the second group comprised a medium plasticity artificial bentonite-sand mixture and a natural clayey soil.

The low plasticity kaolin-sand mixture named K15 was formed by mixing oven-dried sand (S7) with 15% commercially available kaolin. S7 is a subangular quartz sand with a specific gravity of 2.65 and minimum and maximum dry densities of 1.23 and 1.57 g/cm^3, a mean diameter of 0.14 mm, and a uniformity coefficient of 2.1. The plastic and liquid limits of K15 were measured to be 22.8 and 25.9 respectively. The low plasticity illite-sand mixture labeled I15 was prepared by mixing oven-dried sand (S7) with 15% commercially available

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Fig. 1. A view of the Terano landslide. Tr: sampling point for soil Tr.

illite. The Atterberg limits of I15 were as follows: plastic limit — 19.7, and liquid limit — 23.2.

To form a bentonite-sand mixture named B11, sodium bentonite was mixed with silica sand S7. The 11% of bentonite used was enough to produce a mixture with plastic and liquid limits to be 25.7 and 41.0, respectively. The plastic clayey soil Tr (clay content $\approx$ 12%) was recovered from the sliding surface of the Terano landslide triggered by the 2004 Mid-Niigata Prefecture earthquake, Japan (Fig. 1). The detailed description of this landslide was given by Sassa (2005), and Chigira and Yagi (2006). The plastic and liquid limits of Tr were measured to be 25.5 and 45.6 respectively.

Ring-shear apparatus

A ring-shear apparatus (DPRI-4), which was developed at the Disaster Prevention Research Institute, Kyoto University, Japan, was used in this study to carry out undrained cyclic shear stress-controlled tests. The structure of 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 (Sassa et al. 2005, Gratchev et al. 2006b). For this reason, only a brief introduction of DPRI-4 will be given below.

The main features of this apparatus, distinguishing it from other types, are the structure of its undrained shear box measuring 210 mm and 290 mm in the inner and outer diameters, respectively, and the servo-controlled dynamic loading system which enables undrained cyclic shear loading. The sample in the ring-shear box is laterally confined between pairs of upper and lower confining rings, showing the shape of a doughnut. The sample is loaded normally through an annular loading platen. During cyclic loading, shear stress is applied to the lower, rotatable part of the shear box by the torque-controlled servomotor, while the upper part is kept steady by means of two retaining torque arms, with which the shear resistance is measured. Two personal computers are set for test control and data recording. A test can be carried out using either shear stress control (or also referred to as shear torque control (Sassa et al. 2005)), shear speed control or shear displacement control. Pore water pressure, shear resistance and shear displacement are measured by the transducers and recorded automatically.

Test procedure

The ring-shear test specimens prepared from the artificial mixtures were set into the shear box by dry deposition method (Ishihara 1993) and then saturated by means of carbon dioxide and sulphuric acid (H_2SO_4) to create a range of acidic pH values (pH<7) and sodium hydroxide (NaOH) for a range of alkaline pH values (pH>7). To achieve high saturation values for the low permeability natural soil, the ring-shear test specimens of Tr were first prepared as a slurry, using solutions of H_2SO_4 and NaOH, and then placed into the shear box. The degree of saturation was examined by measuring the B_D value, which was defined as the ratio between the increments of generated pore water pressure (Δu) and normal stress ($\Delta\sigma$) ($B_D = \Delta u/\Delta\sigma$) (Sassa 1985). The ratio for each test was ensured to be more than 0.95, a value that indicated an approximately full saturation. After saturation, all specimens were normally consolidated to a confining stress of 105 kPa. Then, a cyclic

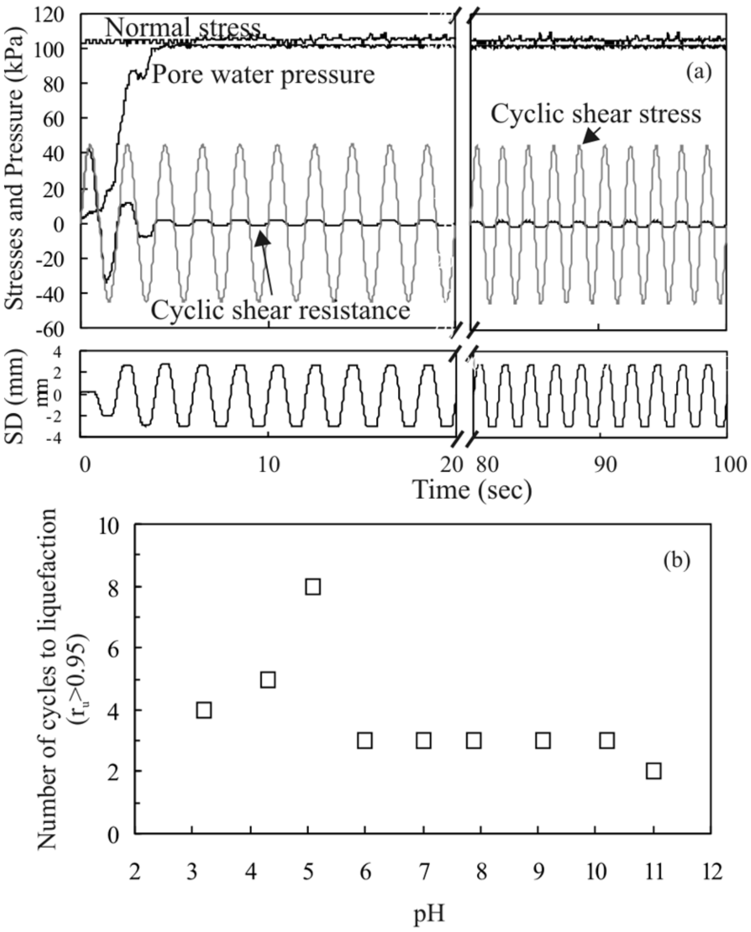

Fig. 2. Results of undrained cyclic shear stress-controlled ring-shear tests on kaolin-sand mixture K15. Time series data (a); and summary plotted as pH against number of cycles to liquefaction (b). (SD: shear displacement).

shear stress with a constant amplitude of about 45 kPa and a loading frequency of 0.5 Hz were applied for 50 cycles.

For the medium plasticity clayey soils the Atterberg limits of the tested specimens were measured after each test: liquid limit was obtained by Casagrande's method, a plastic limit by standard procedure.

To determine whether liquefaction was triggered, a *pore water pressure ratio* (r_u), defined as the ratio of the pore water pressure generated to the normal stress, was used. When r_u was higher than 0.95, the specimen was considered to have liquefied.

Results of tests on artificial low plasticity kaolin, and illite-sand mixtures

The test results obtained for the low plasticity kaolin-sand mixture (K15) in water will be discussed in detail to give an overview of the cyclic response of low plasticity clayey soils in ring-shear tests. As can be seen in Fig. 2a, which is plotted as time series data of normal stress, cyclic shear stress, pore water pressure, cyclic shear resistance and shear displacement, the pore water pressure built up rapidly and nearly reached a value equal to the normal stress in the 3th cycle ($r_u > 0.95$). Concurrently, the cyclic shear resistance decreased to a very small value of almost zero; that is, liquefaction was triggered. The amplitude of shear displacement increased rapidly as pore water pressure generated, and arrived at a steady state when the specimen liquefied.

To examine whether the undrained cyclic behavior of low plasticity kaolin-sand mixture K15 was influenced by pH, a series of tests were conducted at a wide range of pH. The obtained data, which is summarized in Fig. 2b in terms of pH against the number of cycles to liquefaction ($r_u > 0.95$), indicated a small increase in the cyclic strength in an acidic medium. When the pH was below 7, a slightly greater number of cycles was required to trigger liquefaction.

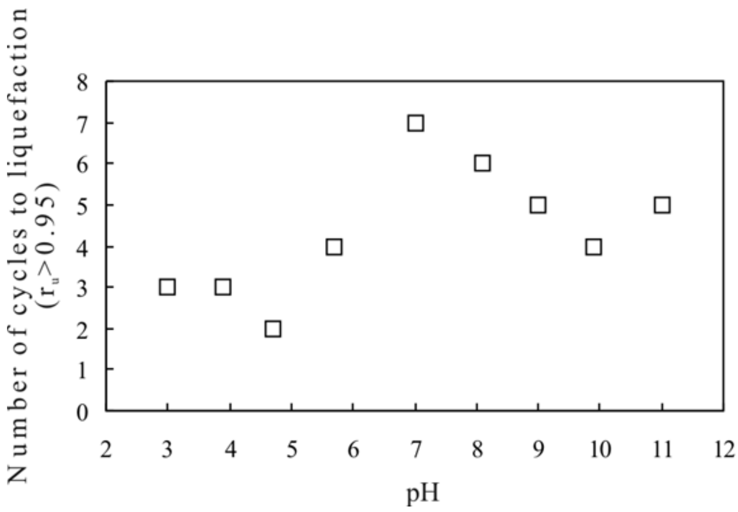

Fig. 3. Results of undrained cyclic shear stress-controlled ring-shear test on illite-sand mixture I15 plotted as pH against number of cycles to liquefaction.

The undrained cyclic response of the low plasticity illite-sand mixture I15 to changes in pH is presented in Fig. 3 in terms of pH against the number of cycles to liquefaction. From this figure, it can be inferred that at pH=7, when the specimen was saturated with water, the liquefaction was triggered after 7 cycles. In an acidic medium (pH< 7), the liquefaction potential of I15 increased, with the average number of cycles necessary to cause liquefaction being equal 3. The liquefaction potential of I15 also increased when the specimens were placed in an alkaline medium. It required about 5 cycles, in average, to trigger liquefaction. In summary, changes in pH can alter the liquefaction potential of low plasticity clay-sand mixtures to some degree. The results showed that for the kaolin-sand mixture, the soil's resistance to liquefaction marginally increased in an acidic medium, while for the illite-sand mixture, it slightly decreased in both acidic and alkaline mediums.

Results of tests on medium plasticity artificial and natural clayey soils

The results of undrained cyclic shear stress-controlled test on the specimen prepared from bentonite-sand mixture in water are plotted in Fig. 4 in terms of time series data of normal stress, cyclic shear stress, pore water pressure, cyclic shear resistance and shear displacement. In this test, the pore water pressure only generated enough to reach a value of about 80 kPa, which was not sufficient to trigger liquefaction. However, changes in pH, as shown in Fig. 5, significantly affect the values of pore water pressure generated (Fig. 5a,b). It is evident that as pH decreased from 7 to 3, ru increased, resulting in liquefaction at pH≈ 3–5 (Fig. 5b). In other words, the soil's resistance to liquefaction decreased as the medium became more acidic. The same tendency was observed for an alkaline medium; that is, an increase in pH values from 7 to 12 resulted in higher values of r_u and the occurrence of liquefaction at pH≈ 8–12 (Fig. 5b). Another interesting finding that needs a special attention is the relationship between plasticity index (PI) and pore water pressure ratio (r_u). It is clear from Fig. 5b,c that a decrease in soil plasticity correlated with the increased values of r_u. As to the variations of PI, it is essential to note that a decline in soil plasticity is generally attributed to clay aggregation (Mesri and Olson 1970), a process that occurs in clayey soils at the microscopic level. The significance of this phenomenon for the liquefaction resistance of clays will be discussed in the following chapter. The response of natural clayey soil Tr to changes in pH (Fig. 6) was quite similar with that of B11; that is, 1) the lowest value of r_u and the greatest resistance to liquefaction were exhibited at pH=7, when the specimen was saturated with water; 2) in acidic and alkaline mediums the liquefaction potential increased (values of ru increased, Fig. 6a,b), as soil plasticity (PI) decreased (Fig. 6c).

In summary, the influence of pH on the cyclic behavior of the studied soils was significant. It was observed that as the medium became more acidic or alkaline, the soil's resistance to liquefaction gradually decreased.

Discussion

In this chapter, an attempt to explain the process behind the observed increase in the liquefaction potential of the medium plasticity bentonite-sand mixture and natural soil will be made on the basis of the

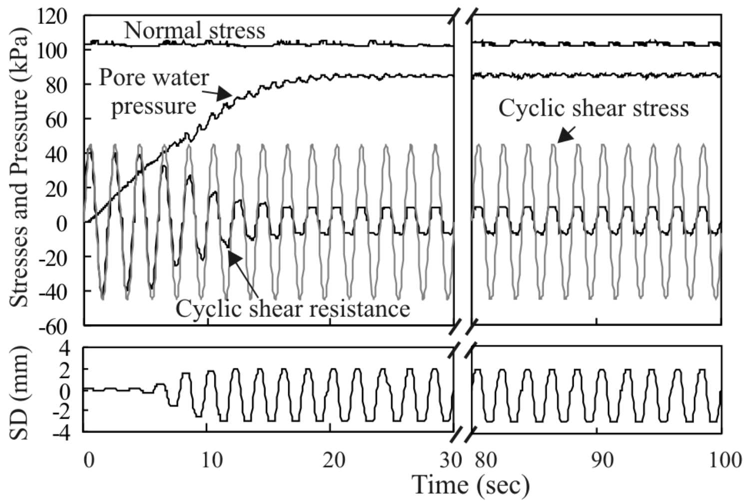

Fig. 4. Results of undrained cyclic shear stress-controlled ring-shear test on bentonite-sand mixture B11 in water.

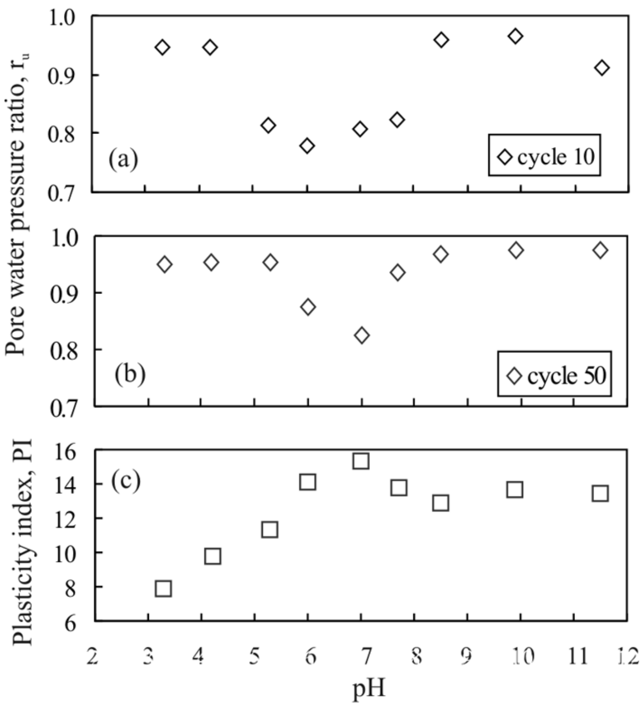

Fig. 5. Results of undrained cyclic shear stress-controlled ring-shear test on bentonite-sand mixture B11 plotted as pH against pore water pressure ratio (r_u) for the 10th (a), and 50th (b) cycle of loading; and pH against plasticity index (c).

principles of colloid chemistry (Olphen 1963). According to the results of several studies (Osipov et al. 1978; Bena et al. 2001), there are two main factors that govern the pH- dependent behavior of clay particles: the clay particle edge charges and the diffuse double layer. It is generally believed that the former is of great importance for kaolinite while the latter prevails in smectite (Mitchell 1993). Nevertheless, it has been experimentally shown for both clay minerals that in an acidic medium (pH< 7) the clay particle edges become positively charged (Fig. 7a), resulting in the flocculated face-to-edge and edge-to-edge arrangement (Fig. 7d), while in an alkaline medium (pH> 7), the predominant clay arrangement is the dispersed face-to-face (Fig. 7f). In a neutral medium (water), clay particles are reportedly arranged in a “honeycomb” structure (Fig. 7c), forming a matrix-like microfabric (Collins and McGown 1974). As previously shown by the authors (Osipov et al.

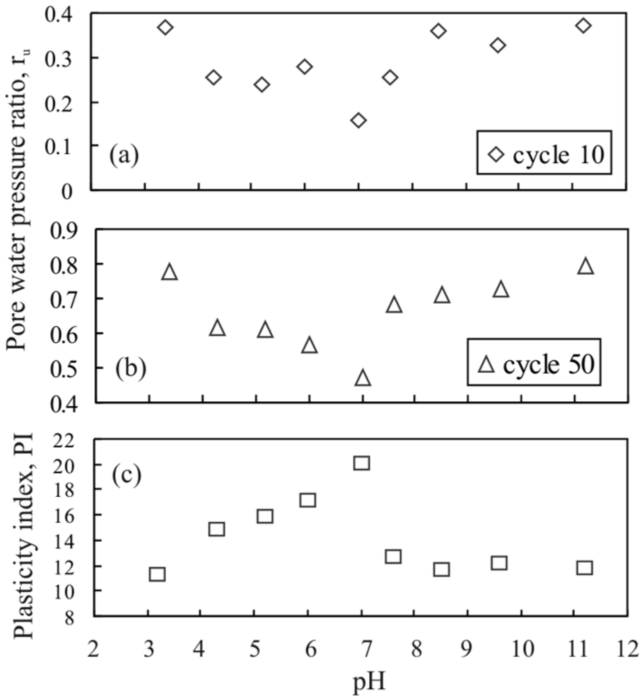

Fig. 6. Results of undrained cyclic shear stress-controlled ring-shear test on natural soil Tr plotted as pH against pore water pressure ratio (r_u) for the 10th (a), and 50th (b) cycle of loading; and pH against plasticity index (c).

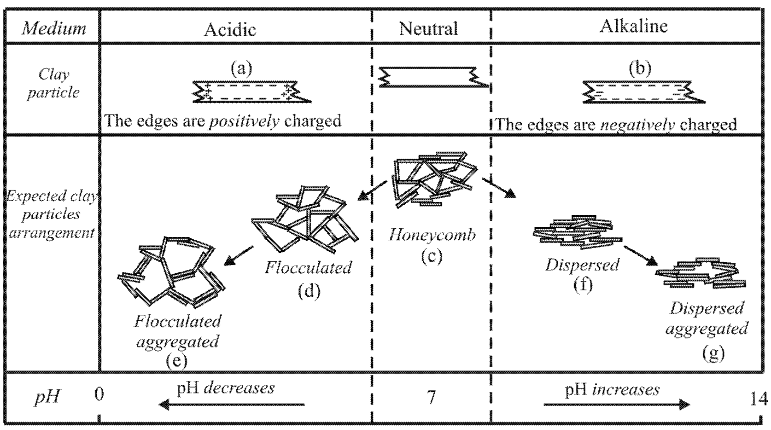

Fig. 7. Schematic clay particles arrangement at different pH.

2005; Gratchev et al. 2006), for specimens of B11 saturated with water, such a honeycomb clay matrix was responsible for the high liquefaction resistance of the mixture. Keeping this in mind, the behavior of B11 at different pH can be interpreted as follows. The change of pH from neutral to acidic resulted in the formation of more open "flocculated" structure (Fig. 7d), an arrangement that resulted in a higher liquefaction potential of soil than the "honeycomb" (Osipov et al. 2005). The further decline in the cyclic strength in proportion to the decreased pH values can be attributed to the process of clay aggregation. The formation of clay aggregates is in agreement with the Gouy-Chapman theory of the diffuse double layer, according to which an increase in electrolyte concentration, in this case H^+ concentration, depresses the thickness of the diffuse double layer of clay particles causing them to aggregate. The resultant flocculated and aggregated microfabric (Fig. 7e) is more open than the flocculated microfabric (Fig. 7d), reflecting on the soil properties: the cyclic strength and soil plasticity decreased. In an alkaline medium, the repulsion between clay particles results in the formation of dispersed structure. The strength of this arrangement is lower than that of the flocculated, according to Lambe (1958), Trollope and Chan (1960), and this property seems to be the main reason for the high values of r_u observed for the specimens of B11 and Tr in an alkaline medium. Further increase in the pH is expected to lead to clay aggregation, transforming the dispersed structure (Fig. 7f) into the dispersed and aggregated (Fig. 7g).

Conclusions

On the basis of the presented results, the following conclusions can be drawn:

1. pH can affect the cyclic behavior of low plasticity kaolin and illite-sand mixtures to some degree. A small increase in soil's resistance to liquefaction was observed for the kaolin-sand mixture in an acidic medium. The liquefaction potential of the illite-sand mixture slightly increased in both acidic and alkaline mediums.

2. For the medium plasticity artificial bentonite-sand mixture and natural clayey soil, the influence of pH on cyclic behavior was found to be significant. The effects were seen in the decreased cyclic strength at low and high pH.

3. The results of this research showed that a small change in pH could affect the cyclic strength of clay. For this reason, it is suggested that the chemical composition of groundwater should be carefully considered in future case studies which include cyclic strength of clay.

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