論文の内容の要旨

Thesis Summary

Evaluation of mechanical properties of sand subjected to piping effect

（内部侵食により連続空隙を有する砂質土供試体の力学特性）

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Internal erosion of soil resulted from piping, seepage or overtopping is the main cause of landslide, dam and levee failures. Internal Erosion refers to the detachment of soil particles from the main soil structure due to the mechanical or the chemical action of a fluid flow. Compare with surface erosion, internal erosion is less studied and harder to quantify, for the reason that only subtle evidence could be observed externally even when severe migration of soil particles has already taken place. Thus, how to predict failure due to internal erosion has become one of the most difficult challenges to both geotechnical engineers and hydraulic engineers.

“Piping” used in this thesis actually refers to a specific internal erosion mechanism, which has been attributed as a cause of approximately half of all dam failures. Piping occurs when water flows through a cavity, crack or other continuous void within the soil. Apparently, the propagation of such internal pipe subject to hydraulic action will directly influence the soil behavior.

Recently, landslides due to piping have occurred frequently in rainy season, such as the disasters in Izu Oshima and Hiroshima in the last two years. Chains of connected macropores, developing nearly parallel to the soil surface, are commonly observed. According to previous studies, such soil pipes is one of the important storm runoff mechanisms on vegetated slope, which has significant impact on the effective hydraulic conductivity and strongly contribute to sediment movement on slopes as well as landslide initiation.

Although it has been identified by many researchers that concentrated leaks (piping) loosens the soil structure and reduces the soil's shear strength, piping effect on soil behaviour has not been quantitatively studied in laboratory by element experiment.

In order to obtain a better understanding of piping effect, an attempt was made in this research to create artificial piping by dissolving water soluble material (glucose) in uniform fine (Toyoura) sand. Plastic straws with different diameters were used to form the regular shape of glucose pipes both in vertical and horizontal. Piping effect was generated when water was infiltrated and drained out through the specimen, leaving loosened sand around the initial pipe. Thus, a new methodology is offered to gain a better insight to the piping phenomenon through mechanical experiments.

The main objective of this research is to evaluate the mechanical properties of sandy soil subjected to localized disturbance. Due to the continuous defect of glucose pipe which forms an erodible flow path, another "inherent anisotropy" appeared in soil. As it is known that anisotropy acts an important role in modelling the shear behavior of sands, in this study, influence of piping-induced anisotropy would be another important issue.

Piping effect is a sophisticated phenomenon as it deals with reformed soil particles with unpredictable structure. With artificially created piping in sand, both the triaxial test and the hollow cylindrical torsional shear tests were conducted. Details about the experiments are introduced as follows.

1. Triaxial compression test

   Quantitative evaluation on mechanical properties of soil subjected to piping effect was achieved by a series of triaxial test for Toyoura sand and Edosaki sand respectively. While the pipe direction was kept as vertical, influence of density, confining pressure, number of pipes was studied. Variation of axial strain, radial strain and volumetric strain during the piping propagation was obtained by LDT and CGs. Young's modulus and Poisson's ratio were evaluated under small cyclic loading before and after loosening. In addition, shear strength variation among specimen with and without pipes were investigated by conducting monotonic compression.

2. Hollow cylindrical torsional shear test

   In order to study the piping-induced anisotropy in more detail, torsional shear tests were conducted both for vertical-pipe-specimen and horizontal-pipe-specimen. With different combination of vertical stress, circumferential stress (equal to radial stress in this study) and shear stress, inclination of the direction of the major principal stress to vertical (α) could be changed continuously. Shear modulus was evaluated with the help of gap sensor under small torsional cyclic loadings, which were applied at initial dry state, after the piping formation, and during the rotation of major principal stress. Moreover, by shearing the specimen under different fixed direction of major principal stress, failure behavior of specimen subjected to piping effect was studied.

Based on the above experimental study, it was found that smaller density samples (initial relative density around 45%) showed larger volumetric strain increment than samples with initial relative density around 75% during the first water infiltration, indicating that loose sand is more vulnerable to progressive deformation during piping formation. For specimens with the initial relative density around 75% in the current research, piping induced volumetric variation was found to be 30%~40% of the initial glucose volume for most cases, which is also influenced by the confining pressure level. A slight larger increase was found in specimen under smaller confining pressure.

The role of fines in piping effect could be clarified to some extent by comparing the results from Toyoura sand and Edosaki sand. In Toyoura sand, piping plane existed as a region where voids with different sizes aligned around the initial glucose pipe in general; while for Edosaki sand, these voids were filled with fines during the water infiltration and the piping plane could be taken as an area with concentrated fines. As a result, different behavior was found in these two sands after piping was formed. Voids in Toyoura sand introduced a new structure with unpredictable properties, especially when checked locally. On the other hand, the rearranged particles in Edosaki sand did not show much piping-induced anisotropy because of the disturbed structure was still uniform in general.

The test results showed that Young's modulus tended to decrease and Poisson's ratio showed a tendency of increase in most specimens with internal pipes after the first water cycle for Toyoura sand. Especially, reduction of shear modulus caused by piping effect showed more dependency on the volume of influenced area compared, in regardless of piping direction.

During the rotation of the major principal direction (α), piping effect was found to have a more obvious influence under α = 90°, in which the reduction of shear modulus show smaller dependency on the variation of normal stresses. For complete rotated α, reductions of G was found in specimen with internal pipes, where a more unstable soil structure was found by the fluctuation of G value against α.

In both triaxial test and torsional shear test, specimen subjected to piping effect showed lower resistance against shear in Toyoura sand. For vertical-pipe-specimen, piping effect in the shear strength was found to be small, possibly due to the end restraint by the top cap and pedestal during the formation of shear band. For horizontal-pipe-specimen, in which the piping plane is coincided with the bedding plane, piping effect on shear strength was more obvious. Existence of piping plane on the development of shear band was also observed in specimen with horizontal pipe, which in turn influenced the shear behavior of the sand.

Surficial failure caused by piping and other factors including poor compaction, saturation, low overburden stress put a great risk on the slope stability. Once soil was detached under the seepage force, global failure might be induced. Since the piping direction in reality always goes with the direction of strata, results obtained from horizontal pipes would be important in predicting the failure of slope or embankment. It is expected that when the potential slip surface directions coincide with the piping planes, a lower strengths would appear. While in this study, a special case of α = 90° was found to be the weakest because of the extreme narrow cross section area in the horizontal direction due to the existence of piping. Therefore, future attention is supposed to be paid on the proper specimen dimension in simulating piping effect.