論文の内容の要旨

Thesis Summary

Comparison of sand behavior under repeated liquefaction in triaxial and shaking table tests

(三軸試験と振動台実験における砂の複数回液状化挙動の比較)

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Liquefaction is a phenomenon wherein soil loses its strength due to cyclic loading; for example, earthquake, and flows in a liquid manner which usually occurs in saturated cohesionless soils. Liquefaction phenomenon was first recognized in the event of Niigata earthquake in Japan in 1964, which vastly caused damage to many civil engineering structures. Since then, the topic of liquefaction interested many geotechnical researchers and practicing engineers.

However, in the past few decades, there have been many reports in many countries such as Japan, New Zealand and Greece that liquefaction took place again at sites where liquefaction had already occurred. This phenomenon is so-called multiple liquefaction, reliquefaction or repeated liquefaction. It is not necessary that repeated liquefaction occurs during the same event of earthquake but also within a long period of time where dissipation of previously generated excess pore water pressure and soil reconsolidation has already done. This can be implied that although sand becomes denser after liquefaction and reconsolidation, soil liquefaction might still likely to occur. Therefore, recently, this issue has been being studied intensively by using both element test and model test; for instance, shaking table test, triaxial test, simple shear test and torsional shear test.

Regarding to repeated liquefaction studies, most of the pioneer works has been focused on using single apparatus and each with different conditions and materials. Thus, results from two major types of test; element test and model test, are difficult to compare. For comparison purpose, although, it cannot be completely concluded that which apparatus is more capable of predicting soil behavior in the field, it is still better to be able to predict soil behavior in model test by having only data of element testing or vice versa. There have been several researchers tried to compare repeated liquefaction behavior between element test and shaking table test. However, the comparison was made by using simplified conventional estimation of stress ratio which depends on the peak amplitude of ground response. Besides, the numbers of liquefaction stage were also limited. For comparative point of view, this thesis is aimed to investigate and compare soil behavior in terms of repeated liquefaction with triaxial and shaking table test using the method of energy approach and cumulative damage concept in comparison. However, in this study, Silica sand with number seven grading which is artificial sand produced from crushed rock was employed instead of Toyoura sand, a Japanese standard sand, due to its availability and high cost as their grain size distributions are similar.

In triaxial testing, three series of test were conducted in order to study three major aspects which were the effect of cyclic stress, the effect of strain history and the effect of small strain history or so-called pre-shearing. For the first series, the specimens were isotropically consolidated to the desired confining pressure before subjecting to repeated liquefaction test with various cyclic stress ratios but constant strain amplitude history ($\varepsilon_{a(DA)}$ = 5%). It was found out that at higher cyclic stress ratio, liquefaction was prone to occur and liquefaction resistance, in terms of number of cycle to cause certain double amplitude strain, increased with liquefaction stages.

For the effect of strain history study, similar to the first test series, but after consolidation, specimens were subjected to cyclic loading with constant cyclic stress ratio but various strain amplitude histories ($\varepsilon_{a(DA)}$ = 1%, 2%, 5%, 7% and 10%). The results showed that repeated liquefaction resistance was greatly affected more by strain history than by relative density. The specimens which were cyclic loaded with lower strain amplitude showed higher liquefaction resistance although an increase in relative density due to reconsolidation was smaller. On the other hand, the specimens with higher strain amplitude history showed lower liquefaction resistance. Nonetheless, the lowest strain amplitude applied to the specimens in this test series was only 1%. Thus, another series of test was conducted to cover the effect of small strain history. In this case, specimens were subjected to small strain amplitude at the first stage of liquefaction (e.g. $\varepsilon_{a(DA)}$ = 0.1%, 0.2% and 0.5%) with constant cyclic stress ratio as the second test series. This small strain history is sometimes called as pre-shearing as the effective stress still does not equal to zero yet; i.e. liquefaction still does not occur. The specimens were then subjected to 2% of strain amplitude in the following stages. Second stage liquefaction resistances of specimens with small pre-shearing history were even larger than that of specimens in second test series. This was another strong evidence that reliquefaction resistance does not correspond well with relative density but strain history. More interestingly, among various small strain histories, the specimen with 0.1% strain history did not show the highest liquefaction resistance as can be expected based on previous finding in the second test series. This behavior can be explained by using energy approach.

In shaking table testing, repeated liquefaction tests were carried out also on the Silica sand which was prepared as an air-pluviated flat ground model consisted of five 10-cm-thick layers. Input motion of 20 sinusoidal cycles with various starting accelerations were applied to the ground model; e.g. 200 gal, 300gal and 400 gal. The input acceleration of the next stage was determined based on the previous liquefaction behavior. If the soil model showed liquefaction, the same acceleration amplitude was repeated in the next liquefaction stage; however, if the soil model did not liquefy, acceleration was raised by 100 gal for the next shaking stage. Ground response was monitored by means of acceleration, pore water pressure and settlement. By employing Newton law of motion and double integration, shear stress and shear strain can be computed. In this manner, similar to triaxial analysis, liquefaction resistance in shaking table can also be calculated in terms of number of cycle to cause target double amplitude strain.

The result of each shaking table test can be divided into repeated liquefaction series under the same input acceleration. The first repeated liquefaction series was during the ground model repeatedly liquefied at starting input acceleration without any increase. When liquefaction stopped to occur at starting acceleration, input acceleration was raised until ground model started to liquefy again. The following series was during when ground model continuously liquefy under constant higher input acceleration. In the each series, it was found that soil liquefaction resistance in the first shake event was always higher than that in the second shake event. However, different in input acceleration also affected liquefaction resistance and number of liquefaction stages. At maximum starting input acceleration of 400 gal, ground model started to liquefy at low number of cycle and continued for 8 stages while only 2 liquefaction stages were observed for the lowest starting input acceleration at 200 gal with higher number of cycle needed to cause liquefaction.

In order to investigate reliquefaction behavior, maximum strain amplitude was calculated for each stage. It was found that future liquefaction can be briefly predicted under the same or lower input acceleration during two stages of liquefaction. It was noticed that lower future liquefaction resistance can be expected in the case where the current liquefaction stage showed higher strain amplitude than the previous one. On the other hand, the liquefaction resistance of the next stage can be expected to be higher when the strain amplitude of current stage is found to be lower than the previous one. It is important to note that, unlike triaxial or other element tests, cyclic stress amplitude and strain history cannot be controlled in shaking table test. Thus, in each liquefaction stage, the model was subjected to various uncontrolled strain history. Even more, the cyclic stress ratio during shaking was not uniform. Thus, it was challenge to compare the result of both tests.

Due to irregular loading response in shaking table test, uniform equivalent stress ratio shall be evaluated in order to compare the both results. Many researchers have tried with conventional method which has some limitations as only the peak stress ratio was taken into the account. It is not only considered too simplified but also, in many cases, liquefaction occurred far earlier before reaching the peak. Some researchers used input acceleration to compute stress ratio which is uniform. However, the ground response during liquefaction is no longer uniform. Thus, using input acceleration may be under or over estimated. This thesis used another method so-called cumulative damage concept. This method was firstly introduced to evaluate fatigue in materials. It assumes that each half pulse of stress ratio gives certain damage to the ground model. When the value of cumulative damage equal to or larger than unity, the failure occurs. Thus, this method allows every stress ratio amplitude before the soil failure or liquefaction to be taken into the account in evaluating uniform equivalent stress ratio. By this manner, relationship between cyclic stress ratio and number of cycle to trigger liquefaction; i.e. liquefaction curve, of shaking table can be drawn. It was found that liquefaction curve of shaking table lies above that of triaxial which can be implied that higher liquefaction resistance was observe in shaking table. Possible reasons such as saturation condition, pore water pressure dissipation and testing conditions were discussed in this thesis.

Further investigation was carried out using energy approach. In geotechnical engineering, during shearing, there is dissipated energy due to sliding mechanism which can be computed based on hysteresis loop of stress-strain relationship. Pioneer works found a virtual boundary which distinguish the amount of dissipated energy to cause positive impact and negative impact resulting in an increase and a decrease in liquefaction resistance of the next stage respectively. Positive impact is defined as amount of dissipated energy during shearing before the stress path crossing phase transformation line (PTL). After the PTL, amount of dissipated energy shall be accounted as negative impact. However, for comparison purpose, because of difference in confining pressure between both tests, modified energy dissipation or normalized dissipated energy by current confining pressure was used. In such a case, modified dissipated energy was calculated based on a hysteresis loop of stress ratio (q/p' or τ/p') and strain relationship. It was found that relationship between positive and negative impact together with the next liquefaction properties was well defined individually for each test apparatus results. However, inconsistence results between shaking table and triaxial was found which might be due to in appropriate virtual boundary.