論 文 の 内 容 の 要 旨

論文題目　Liquefaction characteristics of dense sand specimens with pre-shear histories in torsional shear tests

（せん断履歴のある密な砂供試体のねじりせん断試験における液状化特性）

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Due to cyclic loading during earthquakes, liquefaction occurs in saturated cohesionless soil because of the loss of effective stress. In the 1964 Niigata earthquake, in which huge damage was caused to buildings or structures, the liquefaction phenomenon firstly aroused the attention of soil mechanical scholars. From that time, a lot of study and research has been done on the topic of liquefaction by geotechnical researchers.

In the past, liquefaction was considered to happen easily on the saturated loose sandy ground where the excess pore water pressure is easier to accumulate during cyclic loadings. Thus, in the past few decades, the study of liquefaction was mainly focused on loose sands or medium dense ones. However, with the development of the society, evaluation of liquefaction resistance of saturated dense sands also becomes important especially during the construction of essential structures such as nuclear power plants, large-scale oil tanks, or earth-fill dams. Since this kind of critical structures asks for stable behavior even under large seismic motions, the aseismic design for them should be based on a high acceleration which may be dangerous even for dense sand foundations.

Regarding the study on liquefaction behavior of dense sands, pioneer researchers found very different performance for dense sand samples with similar relative density but obtained by different methods. For example, results of laboratory testing showed that sand specimens obtained by the frozen sampling method from in-situ had better liquefaction resistance than reconstituted specimens prepared in the laboratory. Pioneer researcher considered this phenomenon might be caused by the so called “ageing effect”. During long time period, cementation between sand grains or strain histories brought by earthquakes affected the strength of sands to some extent. For cohesionless sands, the influence of cementation is so negligible that the only possible way for an increase in liquefaction resistance seems to be strain histories.

Study on the influence of strain history or pre-shear history has been conducted for several decades particularly on loose sands or medium dense ones. It has been found that the pre-shear history especially small strain histories could induce significant increase of liquefaction resistance. Therefore, in this study, different types of pre-shear histories were applied to sand specimens prepared by silica sand with the initial relative density of 80% to investigate their influence on liquefaction behavior of dense sands.

In this study, a strain-controlled type of torsional shear apparatus was employed to apply undrained cyclic loading on hollow cylindrical sand specimens. Silica sand with number 7 grading was used to prepare the specimens through the air-pluviation method. After fully saturation by the double vacuum method, sand specimens were consolidated under isotropic condition to the target effective stress before subjecting to cyclic pre-shear loadings in various condition. After the pre-shear, sand specimens were isotropically consolidated again and then subjected to liquefaction test until the double amplitude of shear strain of 7.5% was reached.

For comparison purpose, a series of repeated liquefaction tests with no pre-shear history was carried out. In this series, sand specimens were subjected to cyclic loading with constant double amplitude of shear stress after isotropic consolidation. Drainage and reconsolidation were conducted after 7.5% of double amplitude of shear strain was reached and then cyclic loading was applied again. Results of this series showed that liquefaction resistance increased with liquefaction stages and the liquefaction history in former stage can also be seen as a kind of pre-shear history for the next stage.

Tests with pre-shear history were carried out in 2 different series that distinguished by the drainage condition during pre-shear stages. Pre-shear under drained condition was conducted by controlling the double amplitude of shear strain to be constant with large cyclic numbers. By changing strain amplitude and cyclic numbers in different cases, it was found both parameters could influence the liquefaction resistance. In this series, repeated liquefaction tests were also carried out after the pre-shear and first stage of liquefaction test. It was found that the pre-shear can only affect the liquefaction stage immediately after it.

Another series of tests were conducted with pre-shear history under undrained condition. In this series, cyclic loading during the pre-shear stage was applied until the pore water pressure reached 50% of the initial effective stress. After reconsolidated to the same initial effective stress, this kind of pre-shear was applied several times before the liquefaction test. Results of tests indicated that the number of pre-shear stages could affect the liquefaction resistance significantly. Meanwhile, the effect of pre-shear in different stages can be accumulated.

In order to study the mechanism of the pre-shear effect, further analysis was carried out by means of the dissipated energy concept. During cyclic loading, the dissipated energy can be calculated by integration of the stress-strain relationship. Pioneer researchers has modified this method by normalizing the shear stress by the mean effective stress in order to calculate the normalized dissipated energy. Pioneer studies found that the (normalized) dissipated energy could be distinguished into the positive impact and the negative one which had different effect on the liquefaction resistance. Study on loose sands or medium dense sands considered the phase transformation line as a virtual boundary between these two effects. Before phase transformation, all the dissipated energy is thought to be positive impact while after that, it turns in to negative ones. However, this boundary might be not reasonable for dense sands. In the case of dense sands, due to larger cyclic stress ratio, the phase transformation line is always passed in the first loading cycles. It means when using the phase transformation line as the boundary to distinguish the positive and negative impact, there will be only negative impact left which cannot explain the increase of liquefaction resistance after pre-shear.

Therefore in this study, a new method is considered to distinguish the positive and negative impact during liquefaction tests on dense sand specimens. In this new method, the phase transformation line is still used as a boundary to separate every loading cycle in to three parts. When shear stress is inside the range of two phase transformation lines, the dissipated energy is considered to be positive impact and the rest parts are considered to be negative impact. After calculating the total normalized energy and distinguish it into positive and negative impact, it was found that the positive impact influenced the liquefaction resistance much more significantly than the negative one. Meanwhile, there was a linear relationship between the log of liquefaction resistance (number of cycles to reach 7.5% double amplitude of shear strain) and the log of positive impact.

Further investigation was made by re-analyzing the data from Dr. Aoyagi on medium dense sands to verify the applicability of the new distinguish method. However, although cases with same shear history showed the correlation between liquefaction resistance and the "positive impact", the relationships were not consistent in cases with different shear histories. Then the "net impact" was introduced by considering the "negative impact" on medium dense sand. It was found that with consideration of the negative impact, the relationships between the "normalized net impact" and the liquefaction resistance became more consistent in cases with different histories. It was considered that the "negative impact" had different influence on liquefaction resistance among different density ranges.

The last part of this study is an application of the normalized dissipated energy in predicting the liquefaction resistance curve through a single test. Considering the decrease of effective stress due to the cyclic loading, several points on liquefaction resistance curve can be obtained from a single test. However, due to the influence of former cyclic loadings, the liquefaction resistance of latter points is not accurate. With modification applying the normalized dissipated energy, the liquefaction resistance curve estimated by a single test became better and partly consistent with the typical liquefaction resistance curve obtained by a series of tests. However, further studies are still necessary to improve the accuracy of the modification.