# 博士論文（要約）

Experimental Study on Undrained Cyclic Behavior of Sands Containing Non-Plastic Fines Under Different Stress Conditions
(非塑性シルトを含む砂地盤の非排水せん断挙動に対する異方圧密応力の影響に関する実験的研究)

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# 要約

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Since the problem of liquefaction is known, a lot of work has been done to study the cyclic undrained behavior of clean sands and many criteria have been developed. The effects of relative density, degree of saturation and confining pressure on the liquefaction behavior of the sand are well recognized. So far as the effect of non-plastic fines and consolidation stress ratio are concerned, contradictory results have been reported in past literature from laboratory testing. Simplified procedures developed on the basis of field data and past earthquake induced liquefaction data show an increase in liquefaction strength with increasing fines content. But there is no clear difference mentioned between plastic and non-plastic fines for such simplified procedures. So, based on the available laboratory and field data, the general perception is that the presence of fines increases liquefaction strength of the soil. On the contrary, in the recent large earthquakes (1999 Chi-Chi earthquake, Taiwan; 2010-2011 Christchurch earthquake series, New Zealand; 2011 Great East Japan earthquake, Japan), many sites containing very high percentage of non-plastic fines also liquefied and settlement of houses resting on shallow foundations was witnessed, demanding the

further exploration of the effect of non-plastic fines on cyclic undrained behavior of sands. To study the liquefaction of silty soils in laboratory, different density parameters have been used in the past as parameters of comparison, thus leading to quite contradictory conclusions about the effect of non-plastic fines.

In this study, both drained and undrained simple shear tests were run on reconstituted specimens of two different types of sands and fines with systematic variation of the fines content using hollow cylindrical torsional shear machine. To avoid the confusions observed previously by using density measures as parameters of comparison, constant compaction energy approach for sample preparation was used for the present study. This sample preparation approach closely simulates the soil fabric obtained in natural and reclaimed soils. The testing program was divided into two main parts, i.e. tests conducted under isotropic stress conditions to understand the effect of non-plastic fines on liquefaction behavior of soil under free field level ground surface and under anisotropic stress conditions to observe the role of non-plastic fines on cyclic undrained behavior of soils present below shallow foundations or embankments. The samples were consolidated under 100kPa mean effective stress and some were consolidated under 100kPa vertical effective stress using different consolidation stress paths and were followed by cyclic undrained loading.

For isotropically consolidated specimens, two cyclic stress ratios, CSR (torsional shear stress/mean effective stress), of 0.10 and 0.15 were employed. Volumetric strain developed during consolidation was found to be increasing with increase in the percentage of fines and it was because of the increase in void ratio range ($e_{max} - e_{min}$) with the increase in percentage of fines. During cyclic undrained loading, two important percentages of fines content were identified. First is threshold fines content that exists for the sand~silt mixture having higher particle size ratio, i.e. ratio of mean grain size of sand to that of fines ($D_{50}/d_{50}$), greater than > 6.5. When the fines are less than threshold fines content, the fines just keep filling the empty voids between bigger sand particles without

breaking their particle contacts and hence improve the cyclic strength of the soil. Such threshold fines content could not be observed for sand~silt mixture with lower particle size ratio (<6.5). By contrast, the second important fines content called, limiting fines content was observed for both kinds of soil used in this study. A rapid drop of strength was observed up to limiting fines content, where the fines are assumed to break all the particle contacts between sand particles and no significant effect on liquefaction strength was observed when fines exceeded limiting fines content. Quite similar response was observed for post liquefaction volume change normalized by accumulated shear strain developed during undrained cyclic loading.

The anisotropically consolidated specimens followed different consolidation stress paths to reach mean effective stress of 100kPa and in another series of tests, samples were consolidated to a vertical effective stress of 100kPa. Permanent strain development during consolidation was found to increase with both increase in the percentage of fines content and decrease in consolidation stress ratio. The sand-silt mixture performed well during consolidation upto consolidation stress ratio, $K_c$ (horizontal effective stress/vertical effective stress), of 0.4. As $K_c$ value was further decreased to 0.3, radial dilatancy was observed in clean sand and sand with 10 and 20% fines content, while this radial dilatancy was followed by shear failure for the sand having fines content of 30, 40 and 100%. During cyclic undrained loading, all the anisotropically consolidated specimens could not liquefy and a terminal excess pore water pressure was observed for all the specimens, so the failure was defined by the development of excessive axial strains. By comparing the number of cycles to reach a certain amount of axial strain, it was observed that for all the consolidation stress ratios used in this study, the more was the percentage of fines within a specimen, the faster was the development of axial strain. Although, sand with 10% fines proved to be more resistant to vertical deformation than sand with any other percentage of fines content. When the fines exceeded threshold fines content, there was a rapid drop of strength upto limiting fines content following a relatively less prominent

drop in strength. This behavior was quite similar to the one observed to achieve liquefaction in isotropically consolidated specimens. Post loading volumetric strain normalized by accumulated shear strain also followed a similar trend.

So far as effect of consolidation stress ratio is concerned, it was found to be depending on the reference value of axial strain defined for the comparison. For the tests conducted under constant vertical effective stress to torsional shear stress, a prominent decrease in cyclic strength was observed with the decrease in confining pressure compared to the tests conducted under increasing value of vertical effective stress to torsional shear stress. Based on the observed soil behavior, it was concluded that the magnitude of principal stress ratios is equally important in addition to the principal stress ratio to which the samples were consolidated. So, analyzing the test results in the framework of vertical effective stress by cyclic torsional shear stress provides a better understanding of the observed soil behavior during cyclic undrained loading.

**Keywords: Non-plastic fines, anisotropic consolidation, hollow cylindrical torsional shear machine**