論 文 の 内 容 の 要 旨

論文題目　Experimental Study on Mitigation of Liquefaction-induced Settlement of Structures with Shallow Foundations

（浅い基礎を持つ構造物の液状化・沈下被害を軽減する技術の研究）

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The problem of liquefaction-induced settlement of structures dates back to more than a century ago, during 1906 San Francisco earthquake. However, this issue was overlaid by more serious problems such as vast fire and severe structural damages. It was after 1964 earthquakes of Niigata and Alaska that settlement of structures due to liquefaction captured researchers' attention. From that time, it has been well-documented that almost all earthquakes in liquefaction prone areas are accompanied by structures settlement in liquefied soil (e.g. Dagupan City, Philippines 1990; Chi-Chi, Taiwan, 1999; Kocaeli, Turkey, 1999 and the most recent East Japan and New Zealand earthquakes in 2011).

Numerous studies have been conducted to examine different important factors affecting the mechanism and magnitude of settlement. Outcomes of these studies lead to two different approaches toward treating this problem: 1-structural approach, dealing with supporting structures on deep foundations resting on reliable soil and also strengthening the structural members and 2- Geotechnical approach, in which safety factor of soil liquefaction is increased by applying different measures. These two approaches are applicable to the construction of future structures where financial resources are enough to apply these measures. It is a fact that still many structures are resting upon liquefiable soil. More importantly, installation of expensive structural or geotechnical measures is scarcely possible for private, small, and inexpensive properties.

The recent earthquakes in Japan (2011) and New Zealand (2010-2011) magnified the interest of this problem. Currently there is no world-wide accepted approach toward this issue. For instance, in the case of New Zealand experience, demolishing all structures on liquefiable soil is considered to be the solution. This puts a huge financial pressure on government and people. Moreover, in a highly-populated country like Japan, this cannot be the solution.

This research deals with experimental study on possible protections against this problem. Basically, three countermeasures are proposed: 1- Installation of sheet-pile walls around the foundation of building, 2- Installation of vertical and diagonal drainage pipes around and under the foundation of structure, and 3- Lowering ground water level. The protective mechanism of each mitigation is different. Sheet-pile walls prevent lateral displacement of liquefied soil under the building and consequently reduce the settlement of structure. On the other hand, drainage pipes prevent onset of liquefaction under the building. Lowering ground water level affects the stress distribution of surface structure and decreases the applied pressure on the liquefied sand. It also increases the resistance against punching failure.

Performance of each mitigation and their combinations were examined by conducting shaking table tests. A large soil container of 2.6 meter in length, 0.6 m in depth and 0.4 m in width has been used. Numerous sensors and transducers including pore water pressure transducer, accelerometers, laser displacement transducers and strain gages were installed in the model ground and model structure to record their behavior accurately. It is to be noted that in practice, some areas may originally have low ground water level. Thus, in reporting the experiments results, effects of low ground water level is demonstrated in combination with the other proposed mitigations.

The first series of experiments were conducted to examine the mechanism of building settlement. It was observed that where the model is shaken long enough, the ultimate settlement of structure can be estimated by equilibrium of building's weight and buoyancy force from the liquefied sand. It was also observed that settlement of building causes substantial lateral displacement of liquefied sand. The maximum displacement was occurred at the lower middle depth of liquefiable layer. After this preliminary experiments, the performance of sheet-pile walls against this problem was studied. In practice, liquefiable layer can be so large that reaching the reliable non-liquefiable layer may not be possible. To consider this point, experiments with different fixities at the bottom of sheet-piles were conducted. In addition, fixity of head of sheet-piles was another variable. Stiffness of sheet-pile was the other variable in experiments. In some case a pair of 2 mm aluminum sheets and in some others 1 mm aluminum sheets were used to model sheet-pile walls. It is noteworthy here that based on similitude laws, aluminum sheets of 4mm should be utilized. However, to have more recognizable deformations 1mm and 2mm sheets were used. It implies that as compared with reality, the performance of sheet-piling is underestimated in this study. Ground water level was adjusted at surface, -5 cm, and -10 cm below the surface in different experiments. To reduce the cost of this mitigation, sheet-piling with gaps and short sheet-piling were also examined. Efficiency of sheet-piling against tilting of structures was studied by means of experiments with non-uniform loaded buildings. Based on observation of experiments four governing mechanisms of settlement were defined in different stages of settlement time history: 1- Sedimentation of liquefied sand particles, which occurs in free-field as well. 2- Lateral displacement of liquefied sand and additional sedimentation due to excess pressure of building. 3- Upward flow of liquefied sand and sand ejection through the gap between sheet-piles and building. 4- Formation of water film, which is considered as the dominant mechanism of post-shaking settlement of building. Experimental results have shown that as the lateral displacement of liquefied soil is prevented, the settlement of structure decreases. Constraining the head of sheet-piles from lateral displacement has a great effect on reducing the lateral displacement of liquefied sand. Reaching non-liquefiable layer is a key point for having good performance of sheet-piling. Sheet-piles which did not reach non-liquefiable layer, did not decrease settlement at all. Using stiffer sheet-piles has led to less settlement of model building. Experiments have shown that sheet-piling with gaps do not reduce settlement of building. It was observed that such a sheet-piling may even increase the settlement of building. Because, it disturbs the well-distributed surface pressure of superstructure and changes the mechanism of failure to punching failure through the smooth surface of sheets. Settlement of building was less when ground water level was lower. The same observations were recorded in experiments with sheet-piles and low ground water level. Lowering ground water level also prevents sand ejection from the space between sheet-piles and building. Experiments with non-uniform loaded buildings showed that sheet-piling is not a successful mitigation against tilting of buildings. Data of PWP transducers showed that installation of sheet-piles do not prevent liquefaction under the building. The liquefied sand under the building could deform easily within the constrained area with the sheets and the building tilted consequently.

In the next series of experiments, installation of drainage pipes was examined. Due to the size of soil container and liquefiable layer height, the model ground behaves as in drained condition. However, in reality the height of liquefiable ground provides an undrained condition. It implies that the performance of drainage pipes is overestimated in this study. Configuration of drains is a key parameter in performance of this mitigation. It is observed that installation of vertical drains around the building foundation is not a promising mitigation. However, adding diagonal drainages decreases settlement of structure. Prevention of liquefaction in shallower depths under the building is more important than prevention of liquefaction in the soil surrounding the building and at greater depths. Settlement of building was less where drainage pipes were accompanied by low ground water level. Experiments with sheet-pile walls which were equipped with drainage pipes have shown less settlement than experiments with simple sheet-piles. Since installation of drainage pipes prevents onset of liquefaction under the building, tilting of structure was more mitigated in case of drainage pipes as compared with experiments with sheet-pile walls.

Some complementary experiments were conducted to examine performance of proposed mitigations in more detail. From the viewpoint of similitude law, a series of experiments with Carboxymethyl cellulose (CMC) dissolved in water was conducted. As expected, the settlement of buildings was less in this series of experiment as compared with their representing experiments with water. However, the general observations were the same as experiments with water. In addition, two sets of three-dimensional experiments were conducted. The results of these experiments were also in good agreement with previous experiments. However, there were some differences between 3-D and 2-D experiments results. Unlike 2-D experiments, in 3-D experiments it was possible to have sheet-piles and drainages at all four sides of model building, whereas in 2-D experiments, rigid walls of soil container were at 2 sides of the model building. Finally, three sets of experiments with embedded foundations without any mitigation were conducted. It was observed that the settlement is less where some part of foundation is embedded in ground. Such a observation can be explained by the equilibrium of gravity force of model building and buoyancy force of liquefied sand. In other words, the embedded part of foundation is subjected to some initial buoyancy force which reduces the total settlement of building.

The liquefiable ground is not always smooth and level. Sloping liquefiable ground causes lateral spreading after liquefaction. This can lead to additional settlement and tilting of structures. To reduce lateral spreading of liquefied soil, deep soil mixing is one of the popular methods among engineers. Qualification of this mitigation was examined in the next series of experiments. Effects of change in pattern of improvement, improvement ratio, and length of improvement zone were the variables of this series of experiments. It is noteworthy here that the change of pattern has greater importance. Because unlike the other two variables, it does not bear additional costs to the mitigation work. It is found that change in pattern of improvement reduces lateral spreading of liquefied sand inside the improvement zone. The reduction of lateral spreading of liquefied sand was more clear at several centimeters below the surface of model ground. It is confirmed that increase in length of improvement and improvement ratio also reduces lateral spreading of liquefied sand.

The experiments were simulated mathematically to develop a numerical basis to evaluate the performance of each mitigation numerically. The mathematical solution is based on the principle of minimum potential energy. At the beginning a previously developed solution was employed. Based on that solution the deformation of liquefied soil followed a sine function in vertical axis. In addition, it only considered sheet-piles as fixed bottom and free head. Due to such unrealistic assumptions which affected the results of that solution, a new closed-form solution was developed. In this solution the settlement of building is calculated by minimizing the strain energy of soil, energy of friction, energy of gravity, and strain energy of sheet-pile walls. Time history of subsidence is calculated by solving the equation of motion. The results of the numerical analysis showed good agreement between experimental and mathematical results. The most important advantage of this solution is its simplicity. It requires very basic properties of the site such as weight of building and the depth of liquefiable layer as its input data.

In conclusion and as a summary of all experiments, It was observed that by lowering ground water level for 5cm, including in experiments accompanied by other mitigations or experiments without sheet-piles or drains, settlement of structure reduced around 15cm. It was observed that both installation of sheet-pile walls and drainage pipes also reduced settlement of model building. However, sheet-pile walls are required to reach the non-liquefiable layer at the bottom to show their good performance. Besides, they are not promising mitigation against tilting of structures. In case of drainage pipes, prevention of liquefaction in shallower depths, immediately under the structure is required to have a good performance of them. Finally, It should be kept in mind that based on the sizes of model ground and sheet-pile walls thickness, and considering similitude laws, the results of this study underestimates the performance of sheet-piles and overestimates the performance of drainage pipes.