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Mitigation of seismic settlement of light surface structures by installation of sheet-pile walls around the foundation

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ABSTRACT

Settlement of surface structures, which is particularly a private house, due to subsoil liquefaction is not a new issue in geotechnical engineering. It has been happening during earthquakes in liquefaction-prone areas since many years ago. However, to date no reliable measure against this problem with reasonable cost has been proposed to people. In this paper, results of a series of 1-g shaking table tests which have been conducted to evaluate performance of a possible mitigation against this problem are presented. The proposed mitigation herein is installation of sheet-pile walls around the foundation. In order to reduce the cost of mitigation, sheet-piling with gap and half-length sheet-piling were examined. The experiments were conducted in different ground water levels. It is found out that installing sheet-pile walls in relatively low ground water level can stop settlement of structures completely. Sheet-piling with gaps delays initiation of settlement but it may increase the ultimate settlement of structure. In addition, it is found that formation of a water film under the building's foundation is the governing mechanism of post-shaking settlement of structures.

1. Introduction

Earthquakes in liquefaction-prone areas are usually accompanied by extensive settlement of structures with shallow foundations. The first records of such failures are back in 1906 San Francisco earthquake [19]. However, until the 1964 Niigata and Alaska earthquakes this problem was always overlaid by more serious problems such as extensive fires and severe structural damages. Japan's 2011 great earthquake and New Zealand's earthquakes in 2010 and 2011 showed that this problem can still happen even in countries where geotechnical earthquake engineering research and practice are fairly advanced. Knowledge of geotechnical engineering is progressed enough nowadays to propose promising mitigations against the problem of liquefaction. They can be supporting buildings on deep foundations or improvement of liquefiable ground by several available soil improvement techniques such as compaction, stone columns, and deep mixing. However, still many existing structures are founded on liquefiable soil. This problem has both social and technical aspects. From the social point of view, it is not an economical decision to build residential and inexpensive structures on deep foundations. Moreover, even though people are aware of the liquefaction risk of the ground, they prefer to pay less for ground improvement and thereby reduce land price. Therefore, settlement of these cheap structures becomes a common problem after seismic liquefaction. On the other hand, currently geotechnical engineers cannot propose a reliable and economical mitigation measure to those who have buildings on liquefiable ground. As in New Zealand's case, the government could just buy, demolish and replace houses from hazardous ground. In contrast, in a highly populated country like Japan where the land price is very high, people and government prefer to find some protections against this problem.

To date, research has been mainly devoted to understand the mechanism of building settlement. Yoshimi and Tokimatsu [18] studied different factors which influence the settlement of structure due to liquefaction. They studied effects of contact pressure, soil density, width of the structure, and effect of the embedded wall. Based on their study, they pointed out that the excess pore water pressure ratio decreases as the model structure become heavier. They mentioned increase in width of building reduces its settlement and they reported a considerable decrease in development of excess pore water pressure under the structure by installation of rigid walls on both sides of a model structure. Liu and Dobry [10] studied mechanism of settlement and also effectiveness of sand densification by conducting several centrifuge experiments. They examined normalised settlement of structure with respect to their normalised width. They also mentioned that, by soil compaction under the structure, the settlement deceases while the earthquake

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motion is amplified. Dashti et al. [3] also conducted several shaking table tests and studied mechanism of settlement. They categorised the ground and building settlement into volumetric and deviatoric groups and in each of them several governing mechanisms were listed. They also examined effects of peak ground acceleration, ground's relative density, liquefiable layer thickness, and foundation width. They also proposed and examined effects of some mitigations such as installation of water barriers and rigid walls to reduce settlement of structures [4]. Tsukamoto et al. [16] focused more on the mechanism of rigid circular foundations. They also examined the effects of neighbouring foundation on settlement of buildings. These examples of previous studies show that the mechanism of liquefaction-induced settlement of structure was the main focus of researchers and proposing countermeasures for especially existing structures was not studied as extensively as the mechanism of this problem. However, more recently some studies have been initiated on possible mitigation measures as well. For instance, Kuriki et al. [9] examined efficiency of vertical drains in reducing structure's settlement by conducting centrifuge experiments. Rasouli et al. [13] and Yasuda et al. [17] worked on effects of installation of sheet-pile walls against this problem by conducting shaking table experiments. In this experimental study, based on previous field and research experiences, installation of sheet-pile walls around the foundation is proposed to reduce the settlement of structures. The experiments were conducted with different ground water levels (GWL) to address the effects of lowering GWL as well. Several 1-g shaking table tests were conducted for studying the performance of these measures.

2. Method of shaking table tests

Experiments were conducted using a large soil container of 2.65 m in length, 0.6 m in height, and 0.4 m in width. At both ends of the box shock absorbers made of yarn material and of 2.5 cm thickness were installed. Model ground was made of Silica sand number 7 with properties of $G_s=2.64$, $e_{max}=1.252$ and $e_{min}=0.749$. Fig. 1(a) shows the grain size distribution of this sand. The height of the model ground in all experiments was 50 cm. The bottom 10 cm was considered as non-liquefiable ground and was made by an air pluviation method. This layer was compacted by wooden bars of 5 kg and free-falling of about 10–15 cm. After compaction of this layer, relative density of 80% was achieved. The overlying layers were set to 46% relative density by using a water pluviation method. To achieve this relative density, water level was raised up to 10 cm above the ground and then sand was poured uniformly into the water to make loose layer. These steps were repeated to reach the desired level of liquefiable layer. This study employs only one value of model ground density. In case of lowered GWL, a 2 cm layer of gravel was used at the level of ground water to prevent capillary effect.

In practice, ground water can be lowered artificially by pumping or installation of horizontal underground drains. This drainage network collects underground water at one point. Consequently, GWL of the whole area goes down. For lowering GWL under a single structure there should be less permeable layer under the liquefiable layer, and the ground under the structure should be surrounded by an impervious underground wall to prevent inflow of water from the outside [14]. These technologies for lowering GWL are being planned in many cities in Japan which were damaged by liquefaction in 2011.

In order to observe displacements of ground, vertical and horizontal lines of coloured sand were installed next to the transparent side wall of the box. For making the vertical lines, U-shape aluminium bars were placed near the transparent wall of the box. After finishing each 10 cm layer of ground the vertical coloured sand column was made by pouring sand into the U-shape bar. The aluminium bars were removed after the model ground construction was completed. The horizontal line was installed by pouring coloured sand near the transparent wall after finishing each 10 cm layer. The surface structure was modelled by a wooden box filled with sand. The wooden box had surface dimensions of 38.5 cm × 37.2 cm and weight of 20 kg (1.36 kPa surface pressure). Time history of settlement was recorded by means of a laser displacement transducer. Sheet piles surrounding the foundation were modelled by aluminium plates of 2 mmand 1 mm thickness (with flexure rigidity per width of $EI=47\times10^{-3}$ kN m^2/m and $EI=6\times10^{-3}$ kN m^2/m respectively). Fig. 1(b) shows a schematic view of a typical experiment.

Rasouli et al. [12] studied the effects of fixity of sheet-piles at bottom and top on their performance. Based on that study, when the sheet-pile bottom is fixed and the top is constrained from lateral displacement (free rotation), the settlement of building was the least. In the present series of experiments it is supposed that ground under the liquefiable layer is a stiff and stable layer. Therefore, in all cases the bottom of sheet-piles was fixed from rotation and displacement. Displacement of sheet-pile tops were also prevented by constraining them with metal wire but rotation was possible. There was a gap of about 1 cm between sheet-piles and the model structure. Considerable sand boiling occurs from this gap in cases where the GWL is at surface. This leads to additional settlement of structure [12]. The only exception is the case of half-length sheet-piles where the top of the sheet-pile was fixed to the model building and the bottom was free. In addition,

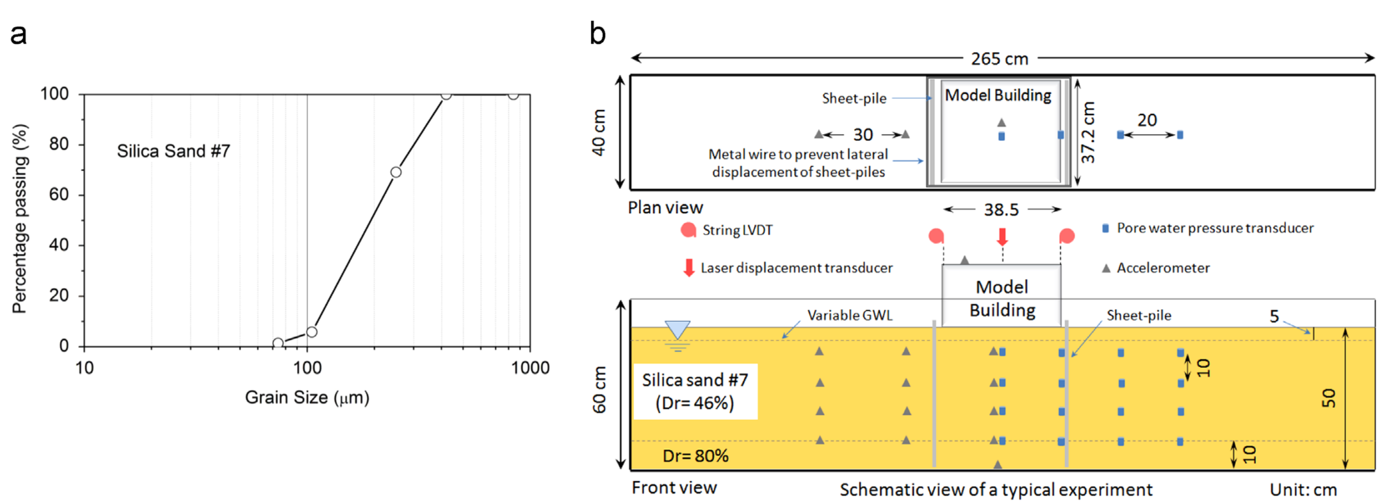

Fig. 1. (a) Particle distribution of silica sand number 7. (b) Schematic diagram of a typical experiment and position of sensors.