Centrifuge model test on behavior of grid-type improved ground subjected to Level 2 earthquake ground motion

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ABSTRACT

The secondary design of building is not mandatorily required in Japan. However, to rationally design the building and minimize the earthquake damage, it is important to consider the secondary design of not only the foundation structure, but also the interaction between the ground and the superstructure. Therefore, as the first step to understand the response of the foundation structure during L2 earthquake motion, we focused on the ground improvement for liquefaction countermeasures. In this research, in order to clarify the mechanical behavior and effect of the liquefaction mitigation subjected to L1 and L2 earthquake ground motions, centrifuge model tests using the soil-cement grid with assumed thickness, area replacement ratio and interval corresponding to the construction site were conducted. The test results show that even if the soil-cement grid is damaged such as cracks, the shear deformation of the improved ground due to subsequent earthquake motion could be partially reduced.

Keywords: secondary design, soil-cement grid, ground improvement, liquefaction, centrifuge model test

1 INTRODUCTION

In the 1995 Southern Hyogo Prefecture Earthquake, the 2011 off the Pacific coast of Tohoku Earthquake and the 2016 Kumamoto Earthquake, a number of buildings were tilted and collapsed due to the foundation structure was damaged by the external force beyond the seismic design force. The 1981 in Japan, the primary and secondary designs of the superstructure were obliged by Enforcement Ordinance of Construction Standard Law. With regard to the foundation structure, the secondary design was obliged in 2001 and only applied in the building evaluated by the time history response analysis. Because the secondary design is not mandatorily required for a lot of buildings at this time, its necessity of the foundation structure considering the interaction between the ground and superstructure is crucially increased to prepare for a huge earthquake would happen in near future.

In the 1964 Niigata Prefecture Chuetsu Earthquake, it was found that the damage of a building using single diaphragm wall as enclosure foundation was slight, while the nearby buildings without enclosure were heavily damaged by soil liquefaction. The soil-cement grid performed better for liquefaction mitigation than single diaphragm wall. It has been well developed in engineering practices as one new liquefaction countermeasure (Sakai and Tazaki, 2003). In addition, the soil-cement grid is also a new remedial measure for earthquake-damaged foundations of high-rise buildings. Up till now, many dynamic centrifuge model tests have been conducted to understand the mechanical behavior of the foundation structure, effect of the ground improvement and seismic response of the liquefiable soil (e.g., Ishikawa and Asaka, 2006; Rayamajhi et al., 2015, Khorasany et al., 2017). However, the mechanism of the soil-cement grid against liquefaction and its performance subjected to L2 earthquake ground motion are still open to question.

In this research, the dynamic centrifuge model tests were conducted to understand the seismic response of the liquefiable soils reinforced by the soil-cement grid and evaluate the residual performance of the improved ground subjected to subsequent earthquakes.

2 CENTRIFUGE MODELS

The schematic view of the centrifuge model ground is...
shown in Fig. 1. It was prepared in a rigid container with internal dimensions of 770 mm × 400 mm × 500 mm under a centrifugal acceleration of 50g, and the model scale is 1/50. Because the gap between the soil-cement grid and rigid box was extremely narrow, Teflon sheet and silicon grease were set on the inside of the rigid box to cut the friction due to the ground motion.

The locations of the acceleration meters (A0V, A0H and A1-7), pore pressure meters (P1-7), strain gauges (SS1-16 and BS1-16), bender element (B1) and laser displacement sensors (L1 and L2) are shown in Fig. 1. In this research, the strain gauges were placed at inner side of the soil-cement grid to understand the mechanical behavior and effect of the ground improvement.

| Test materials | Symbol | Unit | Clayey sand | Coarse sand |
|----------------|--------|------|-------------|-------------|
| Soil particle density | $\rho_s$ | g/cm$^3$ | 2.651 | 2.648 |
| Maximum void ratio | $e_{max}$ | - | 1.143 | 0.801 |
| Minimum void ratio | $e_{min}$ | - | 0.600 | 0.568 |
| Fine fraction content | $F_c$ | % | 14.8 | 0.2 |
| Uniformity coefficient | $U_r$ | - | 40.239 | 1.391 |
| 50% diameter on the grain size diagram | $D_{50}$ | mm | 0.1578 | 1.3100 |
| Permeability | $k$ | m/s | $8.04 \times 10^{-6}$ | $7.14 \times 10^{-7}$ |

2.2 Soil-cement grid

The soil-cement grid, surrounded by the coarse sand, was made of a mixture of water, cement, Fujian sand and Kaolin clay by referring to the previous researches (e.g., Ishikawa and Asaka, 2006; Khosravi et al., 2017; Tamura et al., 2018), as shown in Fig. 3. The water-cement-sand-clay ratio was 1.00 : 0.572 : 1.64 : 0.290 (by weight). The embedded grid, 567 mm (shaking direction) × 384 mm (width) × 300 mm (depth), had six square cells in a 2 × 3 pattern. The thickness of the soil-cement walls and interval was set to 18 mm and 165 mm respectively, so that average area replacement ratio was 25%. The shear wave velocity and unconfined compressive strength of the soil-cement grid were 561 m/s after 12 d and 4.24 MPa after 35 d, respectively.

Fig. 2. Grain size distribution curves of test materials.

Fig. 3. Soil-cement grid after construction.
2.3 Input motions
The centrifuge model ground was subjected to two kinds of sinusoidal sweep wave with the peak acceleration of 0.15g (Case L1) and 0.4g (Case L2) in prototype scale. The motion consists of the first 5 cycles with increasing amplitude, the middle 50 cycles with a constant amplitude at peak acceleration and the last 5 cycles with decreasing amplitude, as shown in Fig. 4. The frequency of the input motion was 1.2 Hz in prototype scale. In Case L2, the same input motion as Case L1 was applied to the centrifuge model ground after first input motion in order to verify the capability of soil-cement grid as liquefaction countermeasures.

Fig. 4. Input motion in centrifuge model tests (Case L2).

3 TEST RESULTS
3.1 Response of acceleration and excess pore water pressure
Figures 5 and 6 shows the time histories of the accelerations and excess pore water pressure ratios in Cases L1 and L2. As shown in Figs. 5 and 6 (b), the base acceleration AX in Case L1 was slightly larger than the input motion. During the first input motion in Case L2, liquefaction caused de-amplification of soil acceleration inside the soil-cement grid, while the acceleration increased to some extent after it comes to the nadir. It implies that the stiffness of the enclosed soil recovered with dissipating the excess pore water pressure. During the second input motion in Case L2, the acceleration of soil was considerably amplified except the top layer which was liquefied. This is because that the amplification response is dependent on the input motion and lower amplitude motion leads to higher amplification.

If pay attention to the excess pore water pressure ratios of the soils at different positions inside of the soil-cement grid in Cases L1 and L2, it is found that the dissipation of the excess pore water pressure was fastened and the peak excess pore pressure ratio was reduced during the second motion especially at deeper depth in Case L2. The liquefaction was occurred in Case L2 during both first and second input motions, but not in Case L1. It can be said that the soil-cement grid is effective as liquefaction countermeasures against the first input motion level in Case L1.

3.2 Shear/bending strain of soil-cement grid and shear strain of ground
Table 2 shows the maximum shear/bending strain of the soil-cement grid due to the first input motion in Cases L1 and L2. As shown in Table 2, it can be seen that the maximum strain of the soil-cement grid in Case L2 was larger than those of Case L1, that is, the soil-cement grid was highly deformed as compared with Case L1. Figure 7 shows the soil-cement grid condition after shaking in Case L2. It is found that the cracks were concentrated on the wall of the soil-cement grid which in a direction perpendicular to the shaking direction.

Fig. 6. Time histories of acceleration and excess pore water pressure ratio in Case L2: (a) 1st input motion, (b) 2nd input motion.
tion and depth. From these results, the maximum shear strain was occurred at the top layer of the ground. If pay attention to Case L2, even if the soil-cement grid is damaged such as cracks, the shear deformation of the ground due to subsequent earthquake motion is partially reduced. In addition, the large settlement of the soil inside of the soil-cement grid was observed after the first input motion, which was also reported by other researchers (e.g., Olarte et al., 2018). It implies that for the improved ground by using the soil-cement grid, the separation of the superstructure from the underlying soil may occur during and after strong earthquake, which will lead to the overloading-induced damage of the soil-cement grid and uneven settlement of the overlying foundation.

2. The liquefaction was occurred in Case L2, but not in Case L1. The soil-cement grid is effective as liquefaction countermeasures against the first input motion level in Case L1.

3. The soil-cement grid was highly deformed as compared with Case L1. Even if the soil-cement grid is damaged such as cracks, the shear deformation of the ground due to subsequent earthquake motion is partially reduced. Boundary condition in this research, however, is more complicated than the dynamic centrifuge model test using the laminar box. In future research, in order to enhance the reliability of this result, more test cases should be conducted.

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**REFERENCES**

1. Ishikawa, A. and Asaka, Y. (2006): Seismic responses of column and grid-type improved grounds, Proceedings of the 6th International Conference on Physical Modelling in Geotechnics, Hong Kong, R. P. China, 521-526.
2. Ishikawa, A., Zhou, Y. G., Shamoto, Y., Mano, H., Chen, Y. M. and Ling, D. S. (2015): Observation of post-liquefaction progressive failure of shallow foundation in centrifuge model tests, *Soils and Foundations*, 55 (6), 1501-1511. DOI: http://dx.doi.org/10.1016/j.soildyn.2015.10.014
3. Khosravi, M., Boulanger, R. W., Wilson, D. W., Olgun, C. G., Tamura, S. and Wang, Y. (2017): Dynamic centrifuge tests of structures with shallow foundations on soft clay reinforced by soil-cement grids, *Soils and Foundations*, 57 (4), 501-513. DOI: http://dx.doi.org/10.1016/j.soildyn.2017.06.002
4. Olarte, J. C., Diashti, S., Lied A. B. and Paramasivam, B. (2018): Effects of drainage control on densification as a liquefaction mitigation technique, *Soil Dynamics and Earthquake Engineering*, 110, 212-231. DOI: https://doi.org/10.1016/j.soildyn.2018.03.018
5. Rayamajhi, D., Tamura, S., Khosravi, M., Boulanger, R. W., Wilson, D. W., Ashford, S. A. and Olgun, C. G. (2015): Dynamic centrifuge tests to evaluate reinforcing mechanisms of soil-cement columns in liquefiable sand, *Journal of Geotechnical and Geoenvironmental Engineering*, 141 (6), 04015015-1-12. DOI: https://doi.org/10.1061/(ASCE)GT.1943-5606.0001298
6. Sakai, K. and Tazaki, K. (2003): Development and applications of diaphragm walling with special section steel - NS-Box, *Tunnelling and Underground Space Technology*, 18 (2-3), 283-289. DOI: https://doi.org/10.1016/S0886-7798(03)00037-3
7. Tamura, S., Khosravi, M., Wilson, D. W., Rayamajhi, D., Boulanger, R. W., Olgun, C. G. and Wang, Y. (2018): A simple method for detecting cracks in soil-cement reinforcement for centrifuge modelling, *International Journal of Physical Modelling in Geotechnics*, 18 (6), 281-289. DOI: https://doi.org/10.1680/jphmg.17.00036