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Shaking Table Tests on Geocell-Based Countermeasures against Pipe Flotation

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ABSTRACT This study investigates the effectiveness of the geocell-based countermeasures against pipe flotation in liquefied ground using shaking table tests. Liquefaction-induced pipe flotation is a significant issue, particularly for agricultural pipelines, which are often installed in areas with high groundwater level. One conventional method that is effective in mitigating this problem is to use geotextiles combined with gravel. However, this conventional method includes challenges in terms of workability, presenting a need for more efficient solutions. A novel approach that employs geocells is proposed in this study. The geocell not only enhances resistance against pipe flotation but also has potential to reduce labor costs. To validate the effectiveness of the proposed method, shaking table tests using an aluminum pipe buried in saturated sand were conducted. In this study, four different experimental cases were conducted: an unreinforced case, a case for the conventional geotextile method, and two cases for the geocell reinforcement. The two geocell reinforcement cases were varied in the method of fixing the geocells and in the backfill material around the pipe. The results demonstrated that all conventional and geocell-reinforced methods significantly reduced pipe flotation compared to the unreinforced method. Compared to the unreinforced case, the geocell reinforcement reduced pipe flotation by up to 24.6 times, and the conventional method reduced it by 13.6 times. In conclusion, the proposed method using geocells to prevent pipe flotation in liquefied ground has been confirmed as an effective alternative to the conventional method.

KEYWORDS Pipeline; Geocell; Liquefaction; Shaking Table Test

1 INTRODUCTION

Buried pipes can suffer significant damages due to pipe flotation caused by earthquake-induced liquefaction. This phenomenon has been reported in many instances, such as the Hokkaido Nansei-Oki Earthquake (Mohri et al., 1995), the Niigata-Chuetsu Earthquake (Yasuda and Kiku, 2006), and the 2011 off the Pacific coast of Tohoku Earthquake (Mohri et al., 2012). Liquefied ground resulting from earthquakes has a high apparent specific gravity, which exerts buoyancy forces on underground structures, causing pipes with lower apparent specific gravity to rise to the surface. For buried pipes in areas with a relatively high groundwater table, such as near rice paddies, it is essential to consider the effects of buoyancy on agricultural pipelines. Specifically, it must be ensured that the combined forces of the weight of the pipes and water, along with the shear resistance of the ground, are sufficient to counteract the upward buoyancy forces acting on the pipes. Approximately 40% of agricultural pipelines in Japan have a diameter of 500 mm or larger (Yamaguchi, 2017). As the diameter increases, the pipes have higher buoyancy forces and must be buried deeper to prevent uplift (Ling et al., 2003). However, burying pipes deeply increases construction costs, backfill material costs, and disposal costs for construction waste soil, as well as extending the construction period. Therefore, it is better to bury pipes as shallow as possible.

To allow shallower burial, many researchers have studied the use of geotextiles and geogrids to reinforce pipes, thereby increasing their resistance to uplift and allowing for shallower burial (Mohri et al., 2015; Maljaei et al., 2022). In Japan, the method proposed by Mohri et al. (1999), which involves encasing the backfill material (gravel) in geotextile on top of the pipe, has been widely adopted as a conventional method against uplift in agricultural pipelines. This conventional method involves spreading gravel on geotextile laid along the pipe and connecting the geotextile at the top of the pipe to integrate the pipe and the gravel, thus increasing resistance to uplift. This method has proven effective (Mohri et al., 1999). To achieve sufficient resistance to the small amount of pipe flotation, gravel must be encased in geotextile under sufficient tension, requiring the geotextile to be laid parallel to the excavation trench. In the case of sheet pile installation, measures must be taken to prevent damage to the geotextile when the sheet piles are removed.

In this study, geocells are looked into as an alternate reinforcement material to geotextiles in order to improve the workability of the countermeasure against pipe flotation. Geocells are transported in a flat, folded state and unfolded on site. The cells are filled with soil or gravel and compacted to form a strong structure. Geocells are installed at the sides and top of the pipe, with the upper and lower parts connected by a belt, which is expected to save labor compared to the conventional method. Another possibility is to integrate the geocell with the pipe by laying geotextile between the layers of the geocell, instead of using a connecting belt, to save even more labor. Push-up tests have been conducted on the buried model pipe to verify that the proposed method has equal or higher resistance to uplift than the conventional method (Nagatani et al., 2024a; Nagatani et al., 2024b). However, the effectiveness of the proposed method in liquefied ground has not been verified. In this study, shaking table tests on a model pipe buried in saturated sand were conducted to verify the effectiveness of the proposed method in preventing pipe flotation in liquefied ground.

2 EXPERIMENTAL PROGRAM

2.1 Model Preparation

A test container made of steel plate with dimensions of 1500 mm in width, 450 mm in depth, and 800 mm in height was used for the test (Figure 1). The front surface of the test container was an acrylic plate to allow observation of the inside of the model ground. The walls of the test container were coated with liquid fluorine to minimize the frictional resistance between the pipe, sand, and the walls. The bottom of the test container was raised approximately 50 mm to allow for water supply.

The model ground was made of silica sand, compacted to a relative density of $D_r = 60\%$. The internal filling materials for the geotextile and the geocell were gravel with a relative density of 80%. The properties and the grain-size distribution of the silica sand and gravel are shown in Table 1 and Figure 2, respectively. Silica sand is classified as poorly graded sand (SP) based on the Unified Soil Classification System (USCS).

The model pipe is a waterproof structure with an outer diameter of 150 mm, a length of 436 mm, and a thickness of 3 mm. The outside of the pipe is made of aluminum, and the inside is made of waterproof Styrofoam. In addition, the waterproof structure was achieved by bonding plates with a diameter of 150 mm and a thickness of 3 mm to both ends of the pipe. The dimensions of the model pipe were set at a 1/4 scale, assuming a medium-diameter pipe with a diameter of 600 mm, which is commonly used as an agricultural pipeline. Sponge tape was attached to the ends of the model pipe to prevent sand from flowing between the pipe and the wall of the test container. The mass of the model pipe was 2.4 kg, giving it an apparent unit weight of 2.96 kN/m^3. In this test, the wire of the displacement transducer (DP-500G, Tokyo Measuring Instruments Laboratory Co., Ltd.) installed on top of the test container was hung on a hook on the top of the pipe to measure the uplift displacement of the pipe during flotation.

The geotextile and geocell models were made at a 1/4 scale. Nonwoven sheets and soft vinyl chloride sheets were selected for their similitude in tensile stiffness. Please refer to previous studies for details of the similitude (Nagatani et al. (2024a, 2024b)). The geocell model is shown in Figure 3, and the physical properties of the nonwoven sheet and soft vinyl chloride sheet are shown in Table 2. The geocell model was fabricated by connecting soft vinyl chloride sheets with cable ties so that the size of the cell when unfolded was 75 mm x 75 mm.

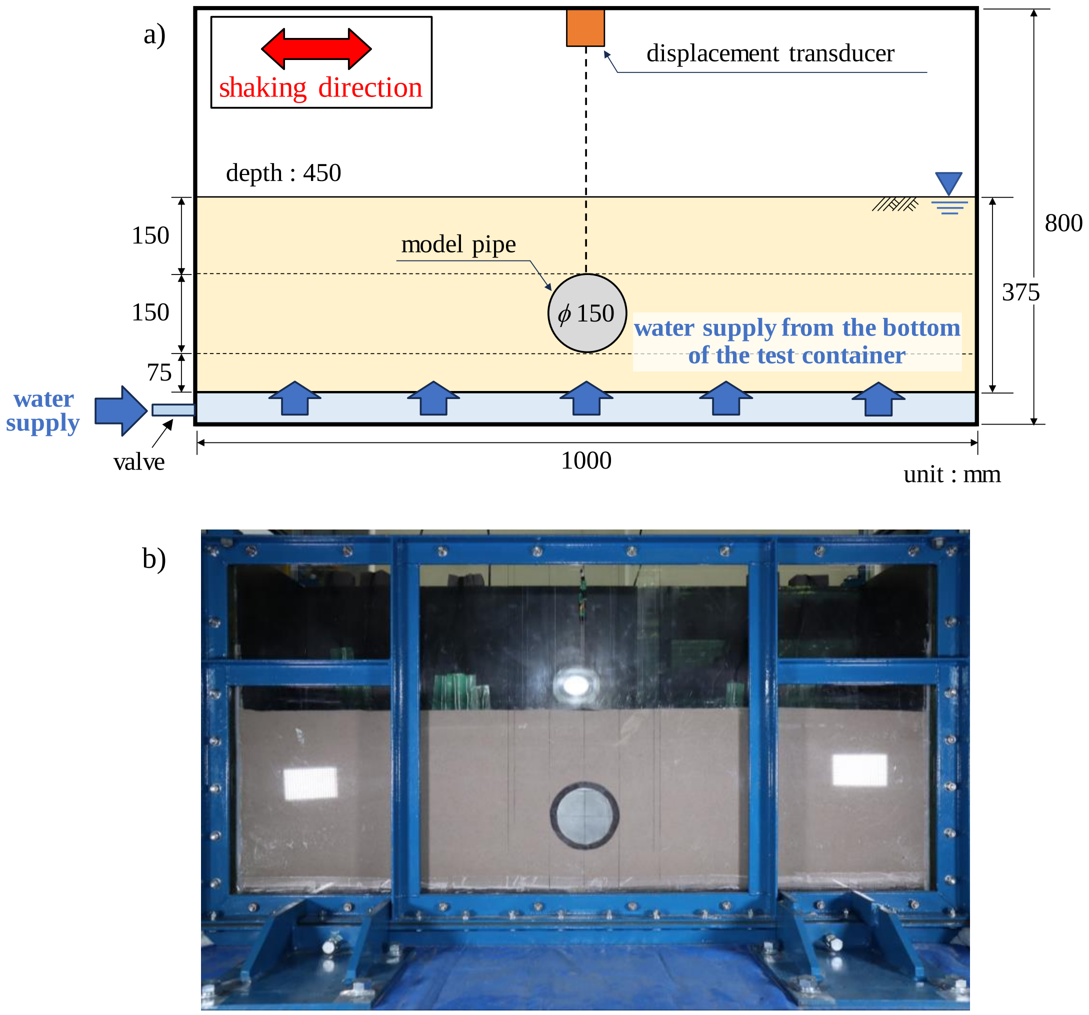

Figure 1. Test container. a) Schematic, b) Photograph.

Table 1. Properties of silica sand and gravel.

parameter	silica sand	gravel
specific gravity of soil particle	2.64	2.73
minimum dry density (g/cm^3)	1.28	1.35
maximum dry density (g/cm^3)	1.61	1.59
mean particle size (mm)	0.29	7.05
uniformity coefficient	2.23	1.61
coefficient of curvature	1.16	0.91
dry unit weight (kN/m^3)	14.28	15.06
saturated unit weight (kN/m^3)	18.68	19.36

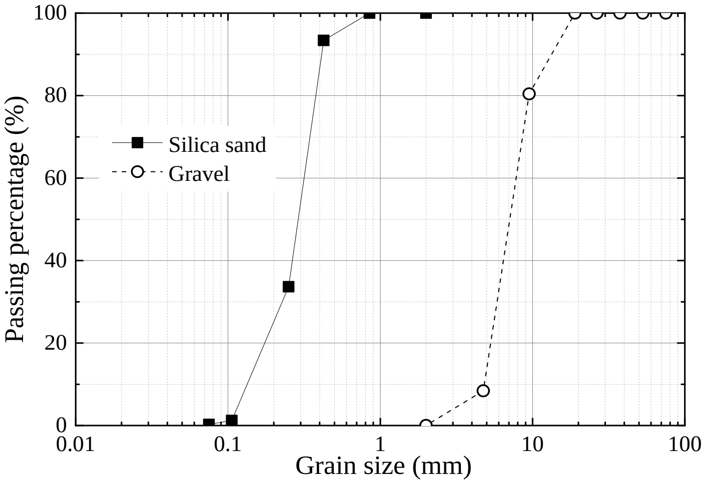

Figure 2. Grain-size distribution of silica sand and gravel (Nagatani et al., 2024b).

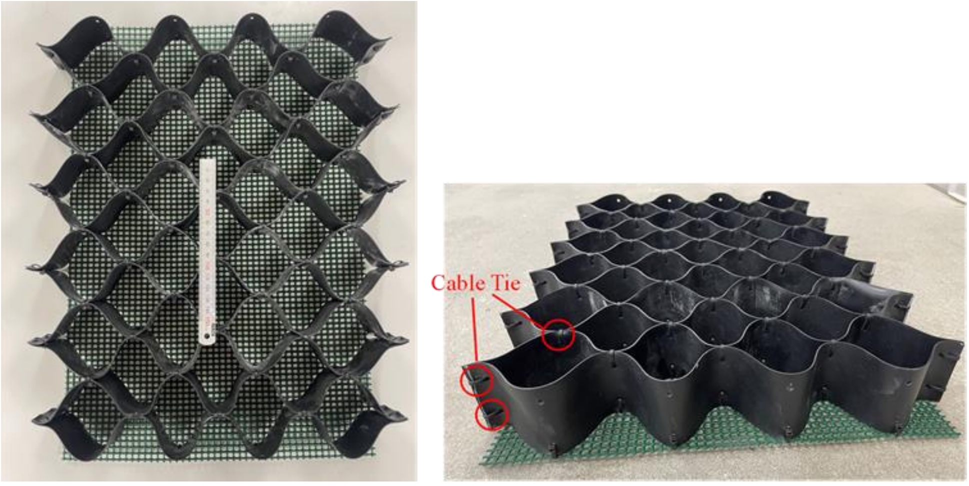

Figure 3. Geocell model (Nagatani et al. 2024a).

Table 2. The physical properties of the nonwoven sheet and soft vinyl chloride sheet.

	nonwoven sheet	soft vinyl chloride sheet
Tensile stiffness at 2 % strain (kN/m)	2.34	0.70
Thickness (mm)	0.34	1.00
Tensile strength (N)	125	101
Mass/unit area (g/m^2)	−	72.7

2.2 Test Cases

The schematic diagram of the test cases conducted is shown in Figure 4. In all cases, the depth of cover above the pipe was standardized to 1.0D (= 150 mm). The height of the cell above the pipe was set to 50 mm considering the scale, and the height of the cells on the side of the pipe was set to 75 mm, which is half the pipe diameter, based on actual construction practices. As shown in Figure 4, a total of four cases were conducted in this study. These include Case 1, which is unreinforced with only the pipe installed; Case 2, which reproduces the conventional method by encasing the gravel in a single nonwoven sheet and fixing it with cable ties; Case 3, where prestressed geocells (geocell structures subjected to pretension before external loads are applied) are achieved by laying nonwoven sheets reproducing geotextiles above and below the geocells and connecting them with cable ties that simulate belts; and Case 4, which involves laying nonwoven sheets above, below, and in the middle layer of the geocells without fixing the geocells with cable ties. In Case 3, the inside of the geocells was filled with gravel, while the space between the cells and the walls of the test container, as well as between the pipe and the cells, were filled with sand. Conversely, in Case 4, not only the inside of the geocells but also the space between the cells and the walls of the test container, as well as between the pipe and the cells, were filled with gravel (Figures 4 and 5).

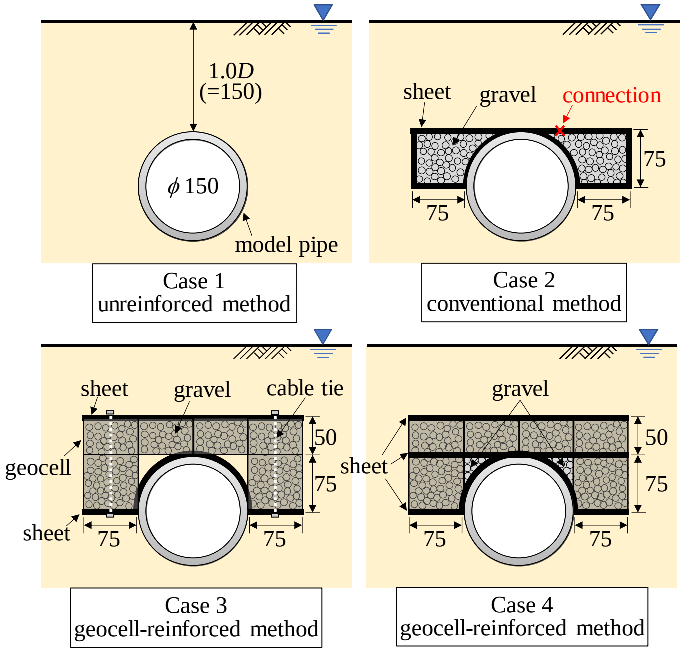

Figure 4. Test cases.

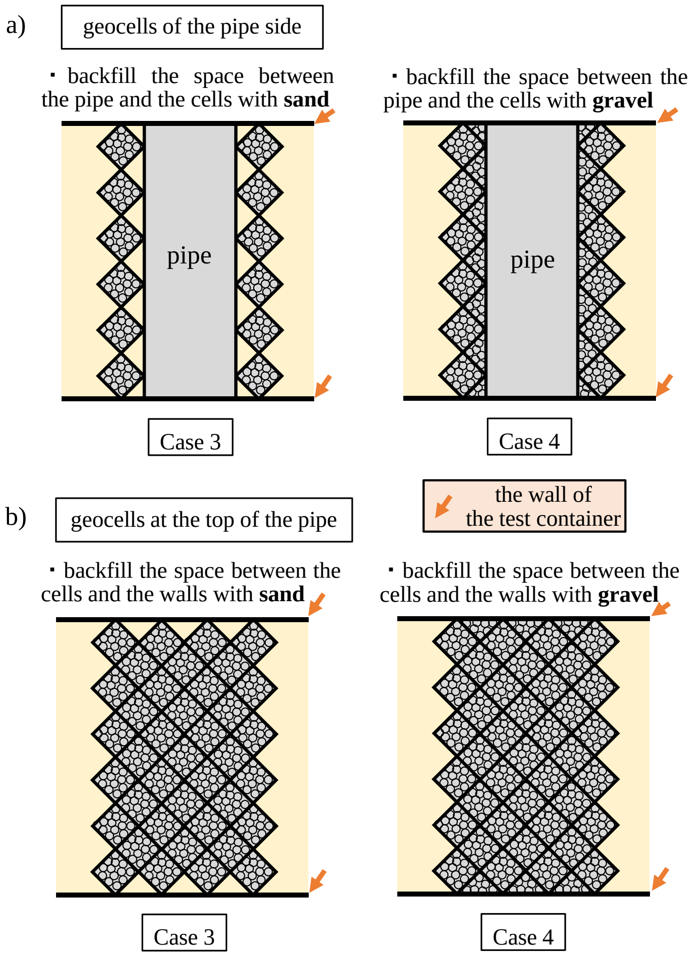

Figure 5. Difference in the filling materials between Case 3 and Case 4. a) Geocell on the pipe side, b) Geocell above the pipe.

2.3 Test Procedure

The model ground was constructed in five layers. For each layer, a prescribed weight of sand was spread out and then compacted using a hand tamper. The height of the ground was carefully managed to achieve a target relative density of 60%. After constructing the model ground, water was supplied from the bottom of the test container to saturate the ground up to the ground surface. Shaking was applied in stages with maximum amplitudes of 200 cm/s², 400 cm/s², 600 cm/s², and 800 cm/s², using a 5 Hz sine wave for 20 seconds each. The direction of the shaking is shown in Figure 1. Figure 6 shows the acceleration of the shaking table obtained in Case 4.

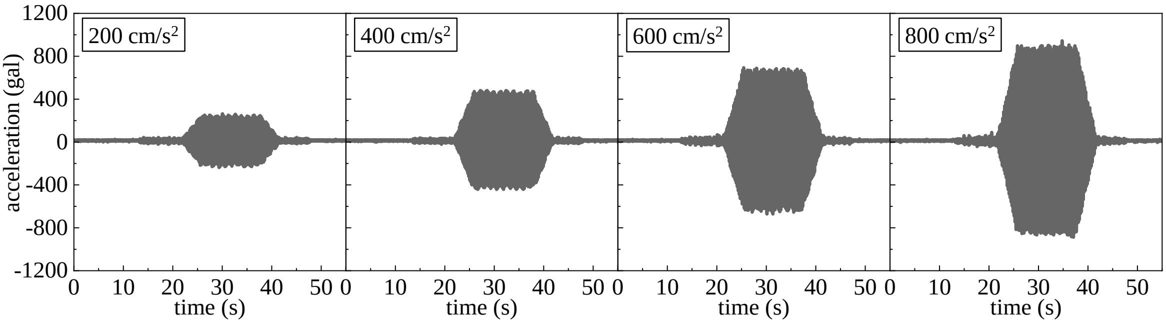

Figure 6. The acceleration of the shaking table (Case 4).

3 RESULTS AND DISCUSSION

3.1 Uplift Displacement of the Pipe During Shaking

Figure 7 shows the changes in the uplift displacement of the pipe over time. From the video taken during the shaking table tests, it was observed that the ground surface undulated during the 600 cm/s^2 and 800 cm/s^2 shaking events in all cases, indicating liquefaction. As shown in Figure 7, in the unreinforced case, the pipe started to show significant uplifted at 400 cm/s^2 shaking stage. At 800 cm/s^2 shaking stage, the uplift displacement reached 150 mm, i.e., the pipe had risen to the original ground surface. In contrast, in Case 3 and Case 4 which geocells were used, and in Case 2 which used the conventional method, the uplift of the pipe was greatly suppressed. Specifically, compared to the unreinforced case, at 800 cm/s^2, the uplift displacement was suppressed by approximately 6.6 times in Case 2, 24.6 times in Case 4, and 13.6 times in Case 3. The experiments have successfully shown the effectiveness of all three countermeasures against pipe flotation.

In Figure 8, the scale of the vertical axis of Figure 7 was changed to compare the three countermeasure methods. In all cases, the pipe did not float at the 200 cm/s^2 shaking stage, but it began to float at the 400 cm/s^2 shaking stage. Additionally, amongst these three cases, Case 3, where geocells were connected vertically, the uplift of the pipe was greatest. This result is different than previous study with pipe push-up tests in dry sand (Nagatani et al., 2024a). In the previous study, the structure with vertically connected geocells (similar to Case 3) had greater uplift resistance than the structure with only nonwoven sheets laid in each layer of the geocell (similar to Case 4). This suggests that, focusing solely on the geocell, Case 3 has a higher uplift prevention effect than Case 4. Therefore, the greater uplift prevention effect observed in Case 4 compared to Case 3 in this study is likely due to differences in the backfilling materials around the model pipe and between the geocell and the walls of the test container.

Furthermore, between Case 2 (the conventional method) and Case 4, where nonwoven sheets were laid in each layer of the geocell, the uplift was slightly more suppressed in Case 2 up to the 400 cm/s^2 shaking stage. However, at the 800 cm/s^2 shaking stage, the uplift was approximately 1.8 times more suppressed in Case 4 than in Case 2. These results demonstrate that countermeasures using geocells are effective even in liquefied saturated ground, especially in Case 4, which involves filling with gravel around the pipe, being particularly effective.

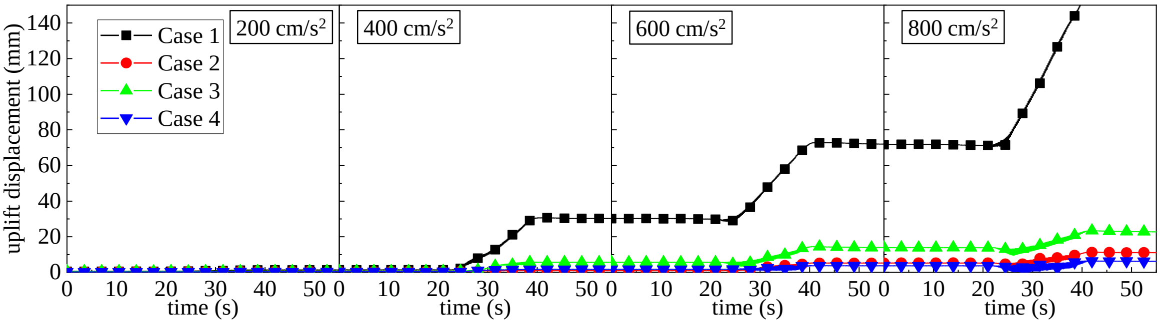

Figure 7. The changes in the uplift displacement of the pipe over time.

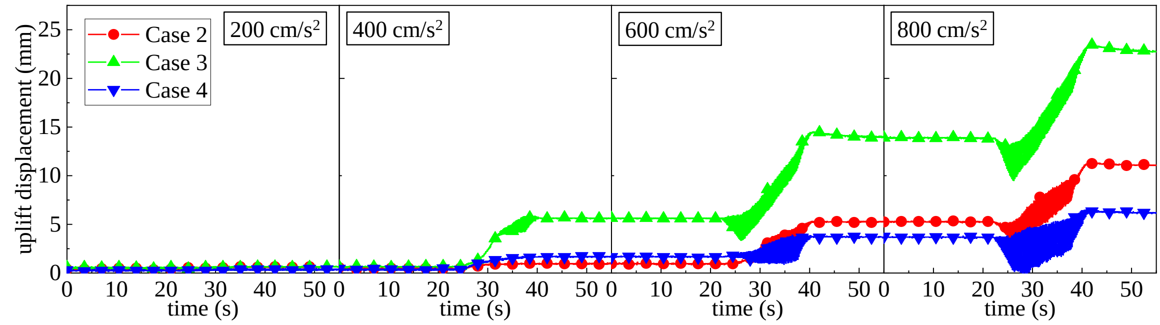

Figure 8. The changes in the uplift displacement of the pipe over time (Zoomed in version of Figure 7 for clarity).

3.2 Shape of Geocells and Nonwoven Sheets after Shaking

Figure 9 shows photographs of the acrylic side of each case after the 800 cm/s^2 shaking. In Cases 3 and 4, sand flowed between the geocell and the acrylic plate, making it difficult to observe the shape of the geocell. Therefore, additional photographs after excavating the sand until the geocell was exposed were taken and shown in Figure 10. From Figure 9, it can be seen that the pipe floated up to near the ground surface for the unreinforced case. On the other hand, from Figures 9 and 10, it is observed that the reinforced areas in Cases 2, 3, and 4 are curved upwards.

Comparing Cases 3 and 4, both using geocells, it is evident that Case 3 exhibits a larger curvature. In Case 3, the geocell was filled with gravel, forming a solid laminated structure. However, since the space between the pipe and the geocell was filled with sand, liquefaction occurred. This caused concentrated loads on the geocell due to the pipe flotation, resulting in significant bending. Conversely, in Case 4, although the geocell layers were not connected and only nonwoven sheets were laid in each layer, liquefaction was prevented because the space between the pipe and the geocell was filled with gravel. As a result, the loads applied to the laminated structure were distributed, and the resistance of the geocell to bending was increased. This indicates that preventing liquefaction between the geocell and the pipe is extremely important.

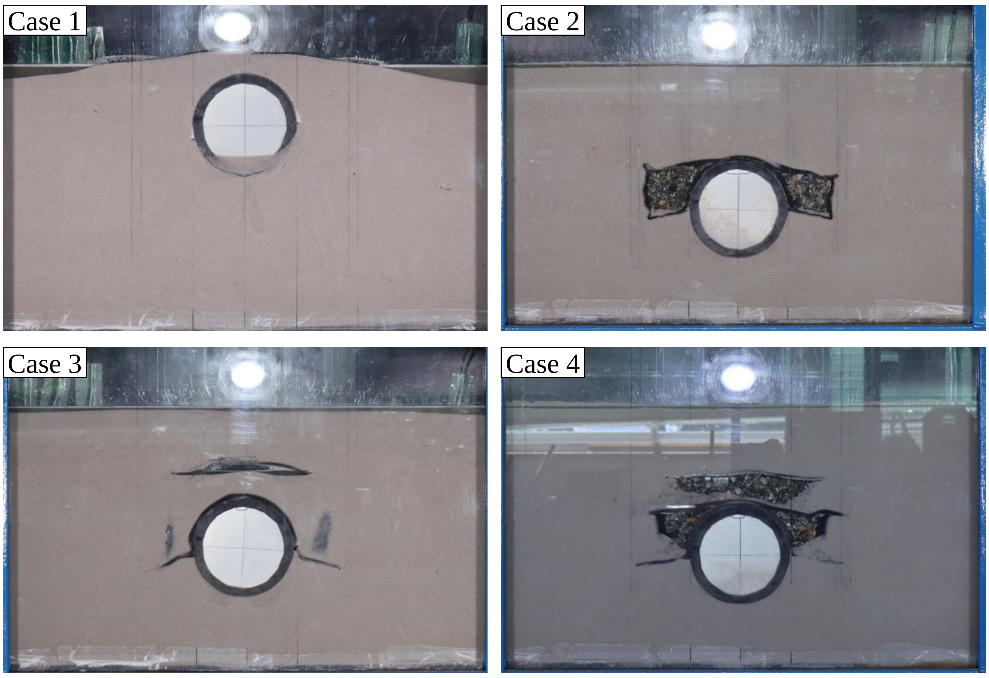

Figure 9. Photographs of the acrylic side of each case after the 800 cm/s^2 shaking.

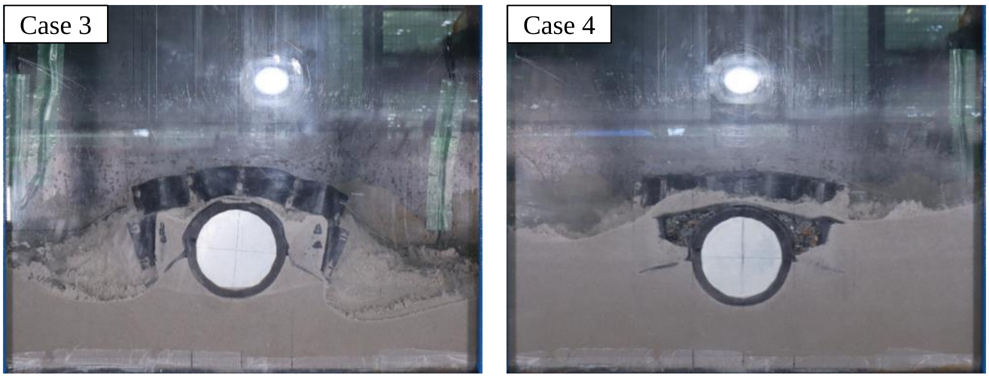

Figure 10. The condition after excavating the sand until the geocell was exposed.

4 CONCLUSION

In this study, shaking table tests using the model pipe were conducted to verify the effectiveness of uplift prevention method using geocells in liquefied ground. The results show that both the conventional method (integrating gravel with nonwoven sheets) and the countermeasures using geocells significantly suppressed the uplift of pipes in liquefied ground. In particular, reinforcement with geocells was approximately 24.6 times more effective in suppressing pipe flotation than without reinforcement. When using geocells, it was also shown that filling the space between the geocell and the pipe with gravel rather than sand has higher liquefaction resistance despite not having vertical connection between two geocell layers. Thus, it can be concluded that the fill material plays a more important role for preventing pipe flotation than the structure of the geocell itself.

DISCLAIMER

The authors declare that Shuji Ito (co-author) and Yutaka Sawada (corresponding author) have a patent pending on this research.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Yutaka Sawada (corresponding author) reports financial support was provided by Maeda Kosen Co., Ltd.

AVAILABILITY OF DATA AND MATERIALS

All data are available from the author.

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