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EFFECTS OF LIQUEFACTION COUNTERMEASURE USING BURIED GABION INSTALLED TO SHALLOW FOUNDATIONS

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ABSTRACT: Liquefaction damage to small buildings, such as detached houses, has been conspicuous in recent earthquake disasters. To mitigate liquefaction damage in residential areas with existing houses, it is reasonable to take measures to mitigate damage to buildings even if liquefaction occurs rather than improving the ground to prevent liquefaction. However, few damage-mitigation measures have been applied to existing buildings. This study proposes a method for mitigating settlement by burying gravel-filled geogrid gabions on the sides of existing or newly constructed foundations. In addition, it evaluates the effect of using gabions to mitigate settlement by shaking table tests using a physical model. The results showed that installing geogrid gabions reduced the settlement of existing strip foundations by 40%-60% compared with that without geogrid gabions. The settlement of the existing mat foundation was reduced by half compared to that without geogrid gabions, depending on the conditions. The gabions were assumed to reduce foundation settlement by locally suppressing liquefaction around the ground.

Keywords: Liquefaction, Shallow foundation, Settlement Mitigation Measure, Gabion

1. INTRODUCTION

The Great East Japan Earthquake of March 2011 caused liquefaction damage to many residential properties in Japan. The number of detached houses that suffered from deformation, such as subsidence and tilting, was 27,000, indicating at lack of liquefaction countermeasures in residential areas [1]. In addition, in 2016, many houses in Kumamoto suffered liquefaction damage [2].

Liquefaction countermeasures are classified into two types: one prevents liquefaction itself, and the other mitigates structural damage of a foundation while allowing liquefaction to occur. Liquefaction prevention methods, such as sand compaction pile methods, have been developed for relatively large-scale sites; therefore, applying these methods to small housing areas tends to be relatively expensive [3]. Hence, when liquefaction prevention methods are applied to a housing area, it is reasonable to cover a larger area; however, it is difficult to obtain agreement among all households in cases where houses have already been built. For example, in Urayasu City, Chiba, Japan, where large-scale liquefaction damage occurred after the 2011 Great East Japan Earthquake, liquefaction prevention measures were planned for approximately 4,100 residential units in the affected area using a grid-form underground wall method. However, after eight years, only 33 residential units were completed [4]. Therefore, when liquefaction countermeasures are applied to a housing area, a method that mitigates structural damage to the foundation while allowing liquefaction to occur is useful because it can be constructed on individual units.

In small buildings, mat foundations are used to mitigate liquefaction-induced settlements [5]. Although a mat foundation does not inhibit liquefaction, it is expected to improve the dispersion of house loads more than the commonly used strip foundation, thereby reducing the deformation and failure of shallow foundations. Laying geogrids larger than the foundation at the bottom of the foundation has also been studied as a stress dispersion method [6].

Methods for mitigating foundation settlement by suppressing the local liquefaction in the ground around the foundation have been studied. For example, Mano et al. [7] examined a method for reducing foundation deformation by replacing the soil around a shallow foundation with gravel in a model experiment. This method was found to be highly effective against foundation tilting owing to the localized liquefaction suppression by highly permeable gravels. Watanabe et al. [8] proposed a method in which the edge of a geogrid laid at the bottom of a shallow foundation was embedded in a gravel replacement area around the outside of the foundation. This method was found to prevent local liquefaction because of gravel replacement and to mitigate foundation settlement because the geogrid at the bottom of the foundation supports the foundation like a hammock.

Because the construction conditions of small-scale buildings vary widely, it is necessary to provide a wide variety of countermeasures to minimize liquefaction damage in housing areas. In particular, all the aforementioned countermeasures [6-8] are designed for newly constructed structures, and there are few economical countermeasure methods for existing structures.

The authors proposed a method that uses buried geogrid gabions filled with gravel on the ground side of a shallow foundation [9,10]. In this method, geogrid gabions filled with highly permeable gravels are expected to prevent local liquefaction around the foundation and support the load at the bottom of the foundation. This method is expected to be applied to new and existing structures. Although previous studies [9,10] have obtained qualitative evidence that this method has a mitigation effect on foundation settlement, quantitative analysis of the mitigation effect has not been performed. Therefore, in this study, the effects of the method using buried gabions on foundation settlement mitigation were quantitatively evaluated by conducting shaking-table tests using a physical model.

This paper first presents the concept of the method using buried gabions. After describing the conditions of shaking-table tests to reproduce the seismic behavior of shallow foundations, the effects of liquefaction countermeasures are discussed based on the results of shaking-table tests.

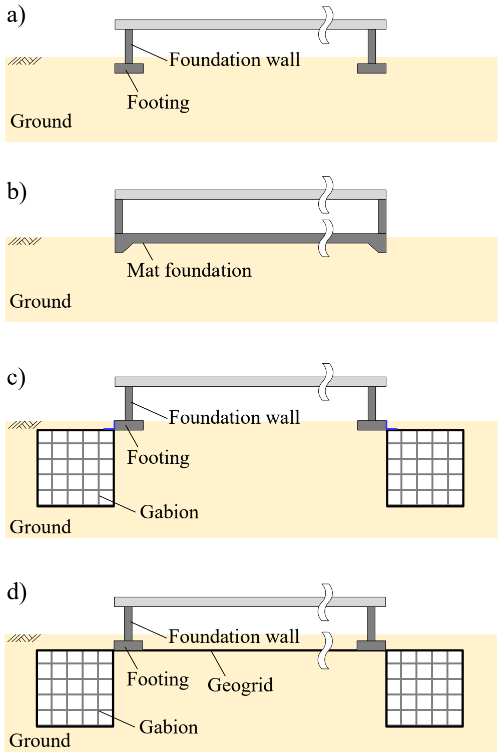

Fig.1 Schematics of the foundation and countermeasures (a) strip foundation, b) mat foundation, c) geogrid gabions applied to existing strip foundation, and d) geogrid gabion applied to strip foundation for new construction).

2. RESEARCH SIGNIFICANCE

Minimizing the deformation and failure of small buildings owing to liquefaction leads to earthquake damage mitigation and rapid reconstruction in urban areas. This study is fundamental research aimed at developing an economical liquefaction countermeasure method applicable to new and existing small buildings. The results obtained in this study might be valuable knowledge to indicate the validity of this liquefaction countermeasure method and to define its development policy for practical application.

3. COUNTERMEASURE USING BURIED GABION FOR SHALLOW FOUNDATION

This study focuses on mitigation measures for shallow foundation settlement owing to ground liquefaction. Figure 1 shows a schematic of the shallow foundations of a small-scale structure. In Japan, strip foundations (Fig. 1a) are typically used for small-scale structures, whereas mat foundations (Fig. 1b) are occasionally used to prevent uneven settlement owing to liquefaction [5]. However, the mat foundation increases its self-weight, which may cause an increase in foundation settlement.

This study investigates a method for preventing shallow foundation settlement owing to liquefaction by buried geogrid gabions on the ground side of shallow foundations. The geogrid gabions consisted of rectangular baskets made of geogrid comprising polypropylene and filled with gravel. Gravel with high permeability was used as the filling material for the basket, which is expected to retain effective stress by dispersing the excess pore water pressure during an earthquake. A previous study revealed that buried geogrid gabions prevent the displacement of buried structures in liquefied ground [11]. A basket made of a polymer geogrid is stable over the long term against environmental events.

When applied to the foundation of an existing structure, geogrid gabions are assumed to be buried in the ground outside the foundation and connected to the foundation to avoid disturbing its lower part of the foundation (Fig. 1c). When applied to the foundation of a new structure, it is assumed that the geogrid gabions are connected to the geogrid laid at the bottom of the foundation.

4. TEST CONDITIONS

4.1 Outline of Shaking Table Tests

Shaking-table tests using a scaled model in a 1G field were conducted in a soil tank with a length of 400 mm, width of 200 mm, and height of 300 mm to evaluate the effects of liquefaction countermeasures using geogrid gabions. The tests focused on the settlement of the foundation and the behavior of the ground when the ground supporting a detached house was liquefied. A schematic of the shaking table test is shown in Fig.2.

Shaking-table tests were performed on shallow strip and mat foundations with and without geogrid gabions. In all tests, the settlement of the foundation model was measured with two laser displacement transducers LD1 and LD2, the excess pore water pressure in the model ground was measured with pore water pressure gauges p1 and p2, and table acceleration was measured with an accelerometer AT, as shown in Fig. 2. LD1 and LD2 were placed at approximately the same horizontal distance from the centerline of the foundation model, and thus the average value of the LD1 and LD2 measurements indicates the settlement at the center of the foundation model. P1 and P2 were placed away from the foundation model so as not to disturb the settlement behavior of the foundation model. The input wave was a 2.0 Hz, 2.0 m/s^2 sine wave, and the shaking time was 10 s. The details of a physical model are as follows.

4.2 Model Details

4.2.1 Similarity law

To rigorously evaluate the behavior of the actual ground and structures using a scaled model, it is necessary to strictly consider the similarity law between the original and the model. However, it is difficult to perfectly reproduce the mechanical and hydraulic properties of the ground in a 1G-field model test using the similarity law.

Based on previous studies [12], at similarity law, often used in shaking table tests in a 1G field, was employed. The similarity laws used in this study are listed in Table 1. The value of λ was set to 105 to reproduce the required ground depth in the soil tank as described below.

4.2.2 Liquefiable ground

The liquefaction potential is evaluated for ground up to a depth of 20 m in residential areas of Japan [13]. To compare the difference in the effect of settlement suppression under ground conditions

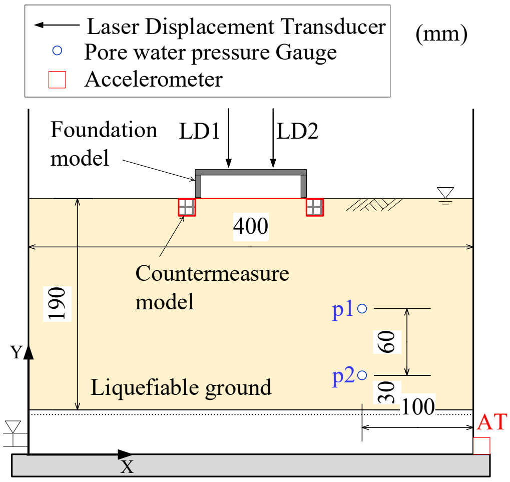

Fig.2 Schematic of shaking table test setting.

Table 1 Similarity rule for model ground.

	Model / Prototype
Length	1/λ
Density	1
Stress	1/λ
Strain	$1/\lambda^{0.5}$
Acceleration	1
Displacement	$1/\lambda^{1.5}$

where foundation deformation easily occurs, the entire area of the model ground, up to 20 m from the ground surface, was set as liquefiable ground. Hence, the thickness of the liquefiable model ground was set to 190 mm by setting the value of λ to 105.

The liquefiable ground was made of Tohoku silica sand No. 7 (soil particle density 25.9 kN/m³, maximum density 15.8 kN/m³, minimum density 12.6 kN/m³) and allowed the dry density to reach 13.8 kN/m³ (relative density 40%) by settling in the water. The particle size distribution of Tohoku silica sand No.7 is shown in Fig.3. The same ground conditions were set for all tests in this study.

4.2.3 Foundation models

The conditions for the foundation models were set assuming a typical detached house in Japan. The weight of a typical house, including its foundation, was set to 770 kN, vertical projected area was 90.0 m², and vertical stress per projected area was 8.57 kPa, as shown in Table 2 by Prototype 1.

Model 1 was set such that the vertical stress per vertical projected area was 1/105 that of Prototype 1. The strip and mat foundation models of Model 1 were prepared to have vertical projected areas and

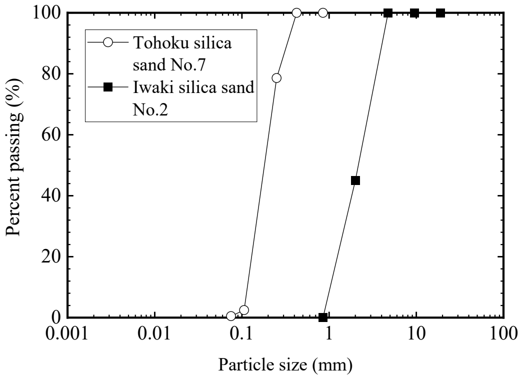

Fig.3 Particle size distributions of geological materials.

Table 2 Conditions of the foundation models.

	Vertical Projected area	Weight	Vertical Stress
Prototype 1	90.0 m^2	770 kN	8.56 kN/m^2
Model 1	0.0190 m^2	1.54 N	81.3 N/m^2
Prototype 2	90.0 m^2	1760 kN	19.5 kN/m^2
Model 2	0.0190 m^2	3.52 N	185 N/m^2

weights, as listed in Table 2. Both foundation models, shown in Fig.4a)–b), were made of aluminum alloy A5052P and modeled in a two-dimensional cross-section with a length of 190 mm.

Model 2, with the same projected area as Model 1 but with a weight of 3.52 N was also prepared by changing the thickness of a model member made of A5052P, as shown in Fig.4 c)–d), to evaluate changes in the behaviors of the foundation and ground model under different loads. The vertical stress per projected area of Model 2 was 185 Pa, which is equivalent to a weight of 1760 kN on a real scale, as shown for Prototype 2 in Table 2.

4.2.4 Countermeasure models

The geogrid gabion on a real scale was assumed to be a rectangular basket with a square cross-section of approximately 1.5 m square and filled with gravel. Hence, the dimensions of the geogrid model were set to a square cross-section of 15 mm square and a length of 190 mm. The basket is made of a polypropylene geogrid. The geogrid was a 4 mm mesh with a tensile strength of approximately 2.5 kN/m.

The filling material was Iwaki silica sand No. 2 (soil particle density 24.0 kN/cm³). The particle size distribution of the Iwaki silica sand No.2 is shown in Fig.2. A stretchable fine-mesh polyester net was inserted inside the basket to prevent the outflow of Iwaki silica sand No. 2. The density of the geogrid gabion model, including the basket and sand, was approximately 13.7 kN/cm³.

The reinforcement method in which geogrid gabions are installed on the existing foundation, as shown in Fig. 1c is called reinforcement Type 1. In type 1, the geogrid gabion model was buried in the side ground of the foundation model and fixed to the foundation model directly at three locations with stainless-steel fixing members with a weight of 0.3 g, as shown in Fig. 4e)–h). Bending deformation of the stainless-steel fixing member was not observed after the shaking table tests.

In contrast, as shown in Fig. 1d), the geogrid gabions installed on the newly constructed foundation are defined as Type 2. In type 2, the geogrid gabion model buried on the side of the foundation model was bonded to the geogrid laid at the bottom of the foundation model using an adhesive, as shown in Fig. 4i). The geogrid at the bottom of the foundation model was identical to that used for the gabion model.

4.3 Test Cases

Table 3 lists the cases of shaking table

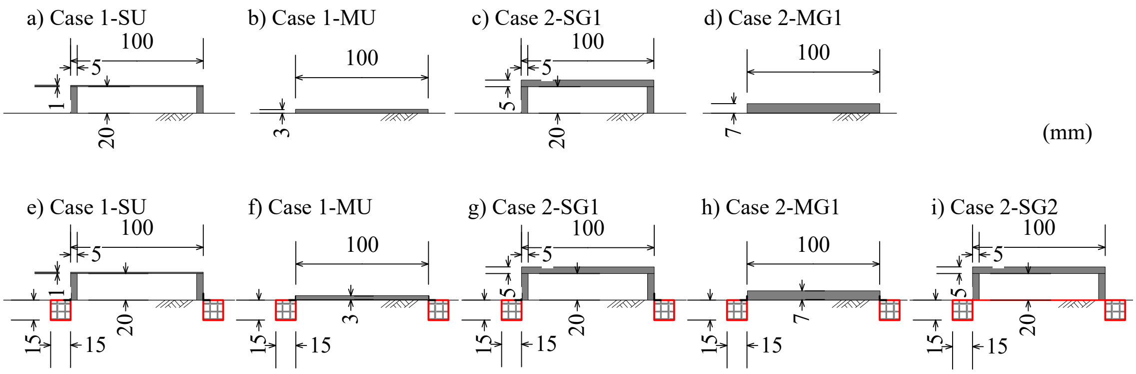

Fig.4 Schematic of physical models of foundations and countermeasures.

Table 3 List of test cases.

Series	Case	Foundation Model	Foundation Type	Reinforcement type
1	1-SU	1	Strip	None
1	1-MU	1	Mat	None
1	1-SG1	1	Strip	Type 1
1	1-MG1	1	Mat	Type 1
2	2-SU	2	Strip	None
2	2-MU	2	Mat	None
2	2-SG1	2	Strip	Type 1
2	2-MG1	2	Mat	Type 1
2	2-SG2	2	Strip	Type 2

experiments. A schematic diagram of the models used in each case is shown in Fig. 4. Tests using model 1 are referred to as Series 1, and those using model 2 as Series 2. The test cases were named according to the following rule: S for the cases with a strip foundation, M for the cases with a mat foundation, U for the cases without geogrid gabion, G1 for the cases with reinforcement type 1, G2 for the case with reinforcement type 2. Because the effect of the difference between reinforcement types 1 and 2 was assumed to be small for a mat foundation, reinforcement type 2 was applied only to a strip foundation in model 2.

5. TEST RESULTS AND DISCUSSIONS

5.1 Time Histories

The time histories of the foundation settlement, excess pore water pressure ratio, and acceleration obtained from the shaking table tests are shown in Fig. 5-6. The foundation settlement is the average value of the LD1 and LD2 measurements, which indicates the settlement at the center of the foundation. The excess pore water pressure ratio was obtained by dividing the excess pore water pressure measured at P1 and P2 by the effective overburden pressure at each measurement point.

5.1.1 Series 1

The excess pore water pressure ratios at P1 and P2 increased to nearly 1.0 during shaking in all cases, indicating that the ground liquefied regardless of the foundation type, with or without gabions (Fig. 5a)). However, the dissipation time of the excess pore water pressure was approximately 5 s faster for the mat foundations (Cases 1-MU and 1-MG1) than for the strip foundations (Cases 1-SU and 1-SG1). Therefore, the foundation type, rather than the gabions, had a greater influence on the

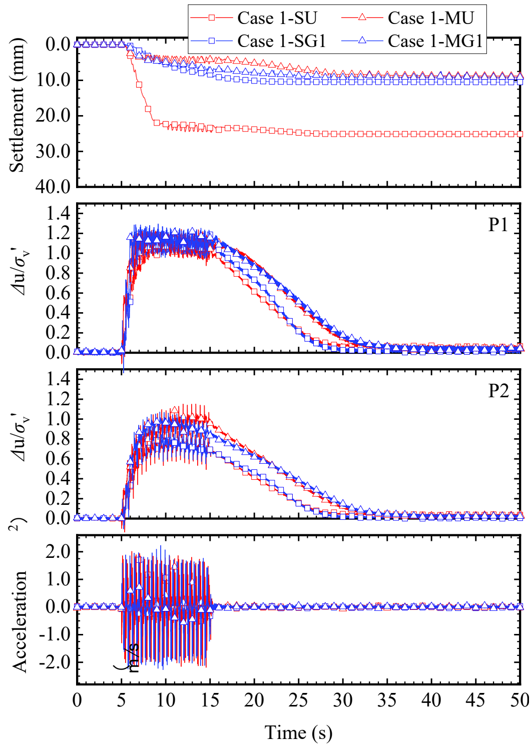

Fig.5 Time histories of measurement results in Series 1.

liquefaction of the entire ground. The reason for the earlier water pressure dissipation of the strip foundation is assumed to be that the excess pore water pressure can be dispersed from the ground surface in the strip foundation model.

In the case of a foundation without gabion, the strip foundation model settled rapidly when the ground liquefied and continued to settle during dissipating the excess pore water pressure (Case 1-SU). However, the mat foundation model settled more slowly during liquefaction, and the residual settlement 35 s after the end of shaking was reduced (Case 1-MU). Although the liquefaction time of the ground was longer in Case MU than in Case SU, as aforementioned, it was assumed that the settlement was reduced for the mat foundation because the weight of the mat foundation was more dispersed than that of the strip foundation.

The strip foundation model with gabions in case 1-SG1 settled slowly, and the amount of residual settlement 35 s after shaking was almost the same as that of the mat foundation model without gabions in case 1-MU. In contrast, the mat foundation with gabions in case 1-MG1 settled earlier than the mat foundation without gabions in case 1-MU. However, the residual settlement was almost the same as that of the mat foundation without gabions. Therefore, the residual settlement mitigation effect of a gabion in series 1 is recognized for a strip foundation but is almost non-existent for a mat foundation.

5.1.2 Series 2

The excess pore water pressure ratios at P1 and P2 increased to nearly 1 during shaking in all cases in series 2, indicating that the ground liquefied regardless of the foundation type, with or without gabions (Fig. 5b)). The dissipation of excess pore water pressure tended to be faster in case 2-MU, probably because the mat foundation model without gabions was buried in the ground immediately after shaking, and the mat foundation model did not block the dissipation of water pressure from the ground surface. Therefore, the dissipation of the excess pore water pressure took longer in case 2-MU than in case 2-MG1. Case 2-SG2, in which the geogrid was laid under the strip foundation, required a longer time for water pressure dissipation after shaking than Case 2-SG1, in which the geogrid was not laid. The geogrid is a mesh, and is not expected to interfere with water pressure dissipation. Thus, the reason for the longer pore water pressure dissipation time in case 2-SG2 was not determined.

In Case 2-SU, the foundation settlement was significantly large to be measured immediately after shaking; therefore, the settlement measured after the test was finished is shown as the settlement at 50 s. Comparing cases 2-SU and 2-SG1, and cases 2-MU and 2-MG1 in Series 2, the amount of settlement decreased regardless of the foundation type when gabions were applied.

In Case 2-SG2, where the geogrid was laid at the bottom of the strip foundation, the settlement was reduced, although it took longer for the water pressure to dissipate than in Case SG2-1, where the geogrid was not laid. This result suggests that the geogrid laid on the bottom of the strip foundation has a settlement-mitigating effect, owing to the dispersion of the load acting on the bottom of the foundations.

5.2 Ground Deformation

Because the difference in the settlement behavior of the foundations under each condition was clearer in Series 2 than in Series 1, the behaviors of the model ground were compared for the tests in Series 2. The behavior of the model ground was evaluated using a marker made of colored Tohoku silica sand No. 7, placed on the side of the soil tank. Figures 7 and 8 show the locations of the markers and foundation and gabion models based on images taken before, immediately after, and 30 s after shaking. The locations of objects that could not be visually confirmed are not indicated.

In Cases 2-SG1 and 2-MG1 (Fig. 7b) and Fig.

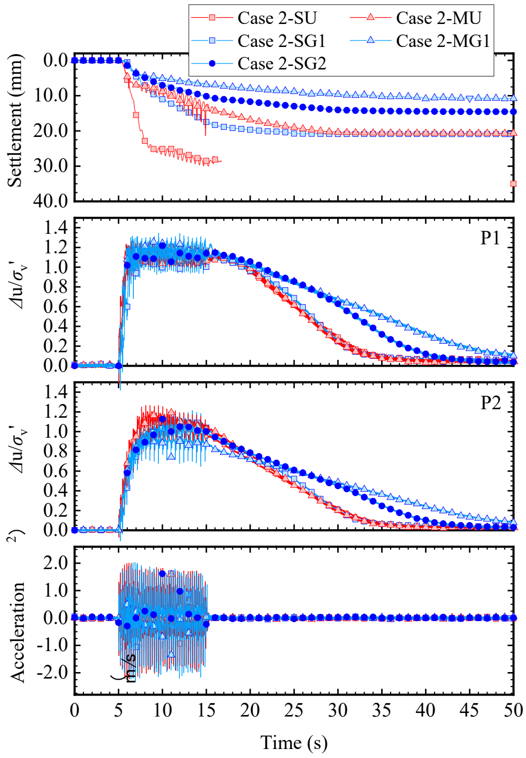

Fig.6 Time histories of measurement results in Series 2.

8b)), where the gabions were installed, the movement of the marker was prevented, especially near the foundation and gabions, whereas in Cases 2-SU and 2-MU (Fig. 7a) and Fig. 8a)), where the gabions were not installed, the marker outside the foundation moved upward as the excess pore water pressure dissipated. Based on the excess pore water pressure measurements shown in Fig. 5, the ground was judged to be liquefied as a whole. However, the prevention of movement of the marker line suggests that liquefaction was partially suppressed in the vicinity of the gabion. Hence, the effects of liquefaction prevention near the gabions are assumed to have prevented settlement in the foundation model in Cases 2-SG1 and 2-MG1.

Comparing Cases 2-SG1 and 2-SG2 (Fig. 7b), c)), the difference in ground behavior with and without the geogrid under the foundation was not well evaluated.

5.3 Effects of Settlement Suppression

Figure 9 shows the relationship between the vertical pressure per projected area and foundation settlement. The settlement of the mat foundation without countermeasures was 42% that of the strip foundation without countermeasures in Series 1 and 60% in Series 2. Note that, these results were

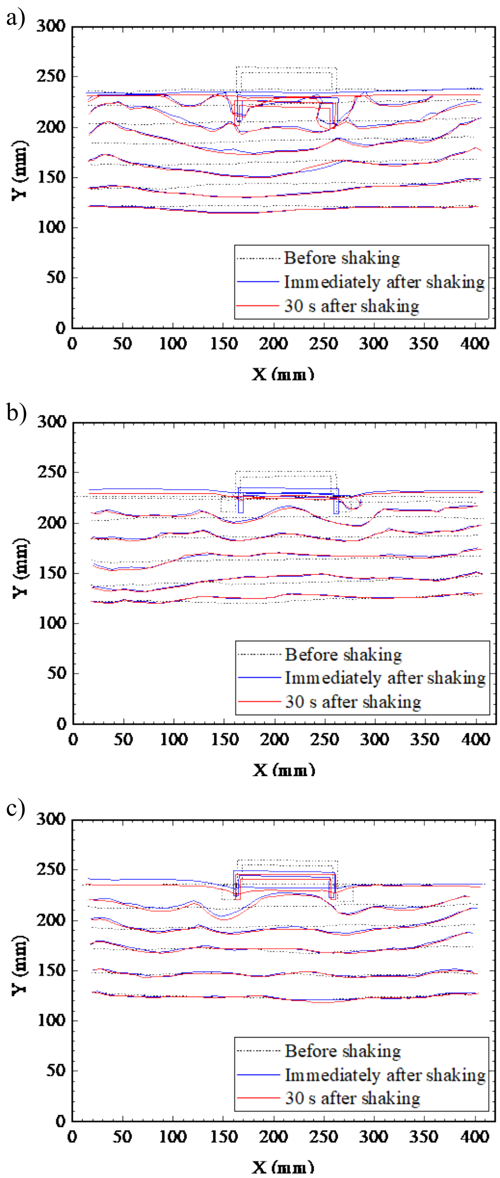

Fig.7 Ground deformation in a) case 2-SU, b) case 2-SG1, and c) case 2-SG2

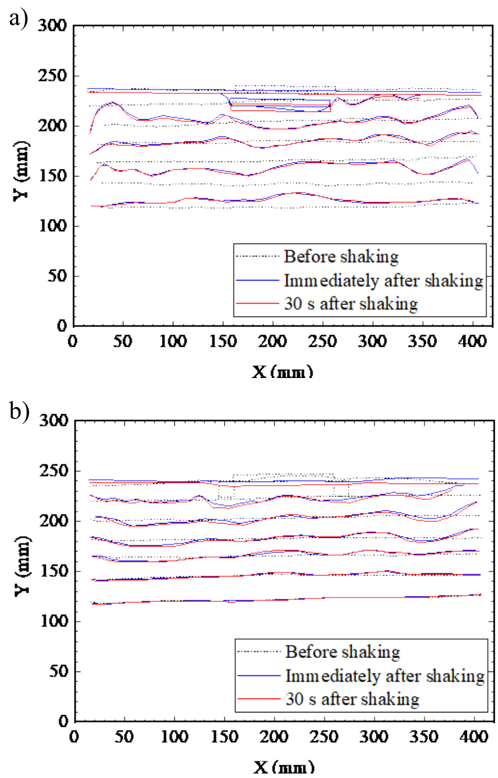

Fig.8 Ground deformation in a) case 2-MU and b) case 2-MG1.

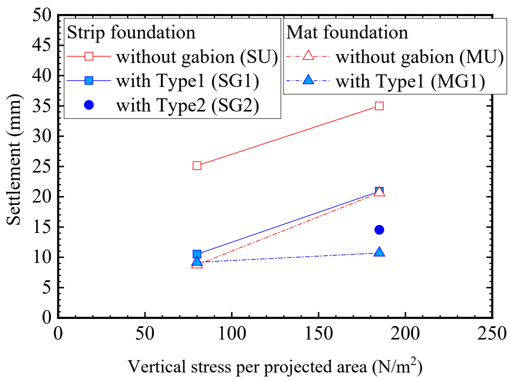

Fig.9 Vertical stress and settlement of foundation model

obtained under the same weight condition as the foundation model, and the weight of a mat foundation is heavier than that of a strip foundation in a real case.

Whereas the settlement of the strip foundation without gabions increased as the vertical pressure increased, the settlement of the strip foundation with gabions was suppressed to the same level as that of the mat foundation without countermeasures regardless of the vertical pressure.

The settlement of the mat foundation without countermeasures increased with the vertical pressure. The settlement of the mat foundation with gabions decreased to 52% that of the mat foundation without gabions in series 2, whereas the settlement of the mat foundation with gabions in series 1 was almost the same as that without gabions. It is suggested that the settlement mitigation effect of gabions may not be strong when the amount of settlement is small without measures; the reason for this requires further investigation.

Based on the excess pore water pressure and ground deformation results, the benefits of installing a geogrid at the bottom of the foundation were not evaluated. However, the settlement of the strip foundation with the geogrid and gabions (case

2-SG2) was 42% that of the strip foundation without countermeasures (case 2-SU). In other words, the settlement mitigation increased by approximately 20% when the geogrid was installed at the bottom of the foundation compared to the case without the geogrid (case 2-SG1). This result suggests that the effect on settlement mitigation is expected to increase with the installation of a geogrid at the bottom of the foundation in a new construction.

6. CONCLUSIONS

The effects of liquefaction countermeasures with gabions on existing and new shallow foundations were examined by shaking-table tests using a physical model. In the tests, a foundation model was placed on liquefiable ground, and the behaviors of the foundation and ground were evaluated when the model ground was liquefied by shaking. The results are summarized as follows.

1) The settlement of the mat foundation without countermeasures was approximately 40% that of the strip foundation without gabions in Series 1 and approximately 60% in Series 2. Note that these results were obtained under the same weight condition of the foundation model.
2) The settlement of the strip foundation with gabions was suppressed to the same extent as that of the mat foundation without gabions, regardless of the vertical pressure.
3) The settlement of the mat foundation with gabions was approximately 50% of that without gabions in Series 2, whereas the settlement of the mat foundation with gabions was almost the same as that without gabions in Series 1. This suggests that the settlement suppression effect of gabions may not be strong when the amount of settlement is small.
4) The ground deformation suggested that liquefaction was partially suppressed in the vicinity of the gabion. The effects of liquefaction prevention near the gabions were assumed to mitigate the settlement of the foundation model.
5) The settlement of the strip foundation with the geogrid and geogrid gabions decreased to approximately 40% of the settlement of the strip foundation without countermeasures. The effect on settlement mitigation is expected to increase with the installation of a geogrid at the bottom of the foundation in a new construction.

In this study, the effects of liquefaction countermeasures were evaluated in the same ground conditions. Future studies are needed to clarify the influences of the ground conditions on the effects of the countermeasures.

7. ACKNOWLEDGMENTS

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