Case study on the deformation control method for embankment during liquefaction by using geosynthetics sandwiched with gravels

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ABSTRACT: A raised embankment structure of 2m tsunami flooding height due to the Nankai Megaquake was planned in the development of parking lots for emergency vehicles by the West Nippon Expressway Company Limited. The reclaimed sandy soil layers with N value of 10 or less are distributed up to a depth of 12 m in this construction site. A liquefaction countermeasure becomes necessary since the ground liquefied and affected the embankment structure when Nankai Megaquake occurs. Although the ground improvement is conventionally used as a main liquefaction countermeasure, it is very costly to install. Considering the use of the parking lot even if sinking due to liquefaction occurs, the selection of construction method is carried out as it is important to suppress unequal settlement and make emergency vehicles to be going out after tsunami flood removed. In this project, the SECURE-G method was firstly adopted which is a structure using geosynthetics sandwiched with gravels was installed under the embankment. The excess pore water pressure around the gravel layer is quickly dissipated due to high water permeability of gravels. Furthermore, the composite structure of gravel with geosynthesis can perform as a rigid beam. As a result, the deformation of embankment is suppressed and its functions are secured. In the design, the deformation of embankment during liquefaction was evaluated using static finite element method (ALID) and the thickness of gravel layer and strength of geosynthetics satisfied the design requirements are decided. The paper describes the design and installation of the liquefaction countermeasure.

Keywords: liquefaction countermeasure, geosynthetics, deformation control, FEM, Construction

1 INTRODUCTION

The Shikoku branch of West Nippon Expressway Company Limited (NEXCO-West) has been carrying out the maintenance of parking lots for emergency vehicles. Even if Nankai Megaquake is occurred, a function allowed to move emergency vehicles is demanded. As shown in Figure 1, huge earthquake in the Nankai Trough has a wide range of envisioned focal area and it also affects to the construction site. In the parking maintenance, a raised embankment of 2m tsunami flooding height was planned. In the stratigraphy structure, the reclaimed sandy soil layers are distributed up to 12 m in depth where liquefaction may occur by Nankai Megaquake and the liquefaction countermeasures becomes necessary. Although the ground improvement methods are generally considered as a main liquefaction countermeasure, the adoptions of those are avoided due to expensive to install. Based on the idea of performance design that permits deformation of the embankment to a level where the emergency vehicles can easily go out, the cheapest countermeasures are considered. As a result, the SECURE-G method was adopted for the first time as a countermeasure which can suppress deformation of embankment due to liquefaction.The standard cross-section of SECURE-G method is expressed in Figure 2. The method is to place a structure using high strength of geosynthetics sandwiched with gravels under the embankment.

Two centrifugal model experiments were carried out in order to confirm the effect of suppression of deformation by countermeasures (SECURE-G).

Not only the research contents but also the design and installation of SECURE-G method as a liquefaction countermeasure being adopted in NEXCO-West are introduced in this paper.

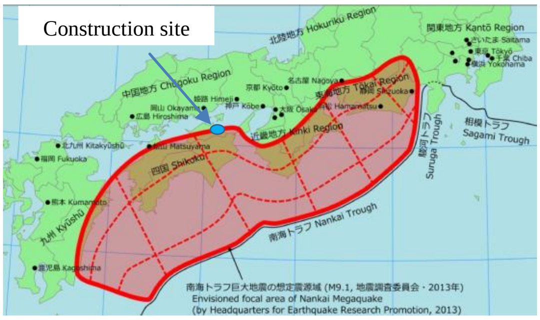


Figure 1. Envisioned focal area of Nankai Megaquake

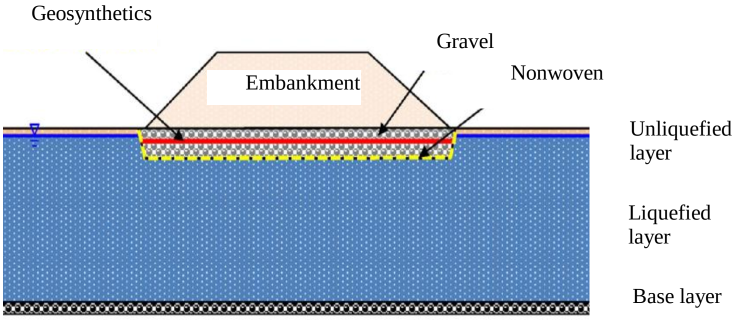


Figure 2. Standard cross-section of SECURE-G method

2 RESEARCH CONTENTS OF SECURE-G METHOD

2.1 *Introduction to centrifugal model experiment-1 (Ookochi et.al., 2011)*

A series of centrifugal model experiments are carried out in order to confirm the effect of SECURE-G method. Those are Case 1 does not use geosynthetics and gravels, Case 2 uses geosynthetics only laid on the boundary between embankment and liquefaction layer and Case 3 uses geosynthetics sandwiched with gravels laid under the embankment. According to experimental result, the effectiveness of SECURE-G method (Case 3) is confirmed by comparing with those of Case 1 and Case 2.

A schematic diagram of SECURE-G in real scale notation is shown in Figure 3.The outline of the experiment is as follows.

- Centrifugal acceleration is 50 G.
- The embankment is 4 m in height, 8 m in width at the top with 1: 1.5 of slope gradient.
- Toyoura sand is used for embankment and its density is about 80%.
- No. 7 silica sand is used for 11m depth of liquefaction layer and its density is about 50%.
- No. 3 silica sand is used for 2.5m depth of base layer and its density is about 90%.
- The areal drop method is used to make the grounds.
- The sheet material with tensile strength (EA) about 60 kN / m is selected by tensile test in 1G field, so that the actual tensile strength becomes 3000 kN / m by taking the similarity rule into consideration.
- Excitation is a sine wave with maximum acceleration of 3.0m/s^2. Its frequency is 1.2 Hz. Excitation sequence is gradually increase the first 10waves towards a constant acceleration of 3m/sec^2, the second 50 waves with constant acceleration and then gradually decrease for the last 10 waves.

Figure 4 shows the settlement distribution of the ground surface and its final deformation pattern of embankment after excitation. The settlement amounts of the shoulder are smaller in order of Case 3 (80cm), Case 2 (100cm) and case1 (120cm). The higher deformation constrain effects is founded in case3.

A clear difference of the settlements at the embankment bottom can be seen in Figure 4. The settlements are 85cm for case1, 80cm for Case 2 and 40cm for Case3. The unequal settlement does not occur in case3 compare with others. Moreover, the lateral displacements of embankment toes are 50cm for case1, 5cm for case2 and 15cm for case3. The lateral displacement constrain effects can be seen in case2 and case3. However, it is noted that the lateral displacements of embankment toes might be affected by the lateral boundary conditions of the chamber.

The distribution of excess pore water pressure ratios are shown in Figure 5 for Case 1and Figure 6 for Case 3. The excess pore water pressure ratio of Case 1 (without countermeasure) is 0.3 to 0.6 just under the embankment center and 0.6 to 0.9 under the embankment toes. On the other hand, the excess pore water pressure ratio of Case 3 (with gravel layer) decreases to 0.0-0.3 just under the embankment center and 0.3-0.4 just under the embankment toes. According to excess pore water pressure distribution, it can be said that the liquefaction degree of case1 is greater than case3. The dissipation effect by the gravel layer was confirmed.

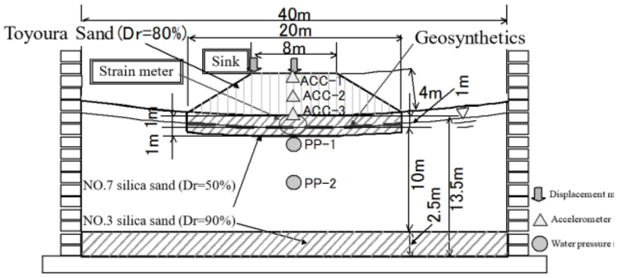


Figure 3. Schematic diagram of SECURE-G

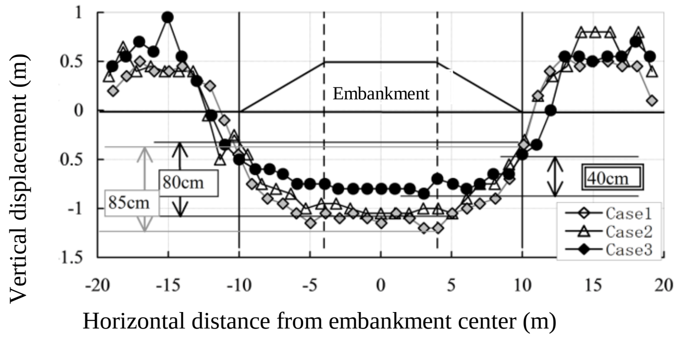


Figure 4. Distribution of ground surface

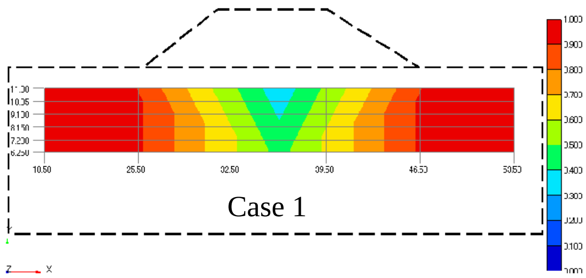


Figure 5. Excess pore water pressure distribution

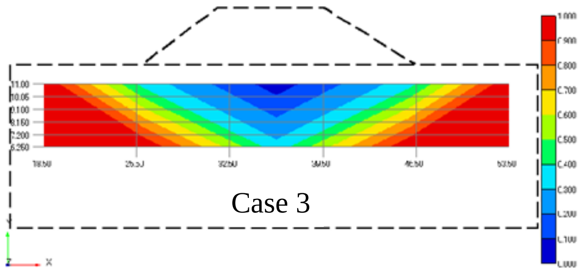


Figure 6. Excess pore water pressure distribution

Introduction to centrifugal model experiment-2 (Takahashi et.al.,2015)

A series of centrifugal model experiments are carried out in order to confirm the effect of SECURE-G method. Those are Case1 does not use geosynthetics and gravels, Case 2 uses gravel only and case3 uses geosynthetics sandwiched with gravels laid under the embankment. According to experimental result, the effectiveness of SECURE-G method is confirmed by comparing with those of Case 1 and Case 2.

A schematic diagram of Case 3 in real scale notation is shown in Figure 7.The outline of the experiment is as follows.

- Centrifugal acceleration is 50 G.
- The embankment is 2 m in height, 4 m in width at the top with 1: 1.5 of slope gradient.
- The DL clay mixed with silicone oil at an initial oil content of 22% is used for embankment. The unit weight of DL clay is 15 kN/m^3.
- Toyoura sand is used for 11m depth of liquefaction layer and its density is about 50%.
- Base layer (non-liquefaction layer) is set under the liquefaction layer.
- The sheet material with tensile strength (EA) about 60 kN / m is selected by tensile test in 1G field, so that the actual tensile strength becomes 3000 kN / m by taking the similarity rule into consideration.
- The amplitude-adjusted seismic wave (IBR006, NS component) observed at K-Net Mito during the 2011 Tohoku region Pacific Offshore Earthquake is used as input wave.

The settlement amount of the embankment crest with time history is shown in Figure-8. The settlement amount of the embankment crest at the end of main movement point of 120 s was smaller in the order of Case 3 (267 mm), Case 2 (316 mm) and Case 1 (434 mm). The higher deformation constrain effect is found in case3.

A ground deformation diagram showing pre- (black line) and post-excitation (red line) are shown in Fig. 9. In Case 1, the liquefied ground deforms laterally at the ground surface portion and the bottom of the embankment deforms largely in an arc shape. In Case 2, lateral deformation near the ground surface is constrained as compared with case1, but it occurs at a deep position of the ground and a slight unequal settlement can be seen at the bottom of the embankment. In Case 3, the lateral deformation near the ground surface is small and the deformation of the bottom of the embankment is deformed in a substantially uniform vertical direction compared to case2. It is due to restraining the bending deformation of the gavel layer with sandwiched geosynthetics in the gravel layer behaving such a rigid beam. It can be thought that it is the suppressing effects on the lateral deformation and unequal settlement by SECURE-G method.

The excess pore water pressure ratio and the liquefaction resistance value FL at the time of major excitation are shown in Figure10. The values of FL at the upper part of liquefied ground in case1 are 0.6and 1.45 at near the embankment toes and center. The values of FL at the upper part of liquefied ground in case3 are 0.96 and 2.20 at near the embankment toes and center. As a result, it is confirmed that the value of FL around the gravel layer increased to form an incomplete liquefaction layer. The liquefaction resistance FL of incomplete liquefaction zone is 1.2 which is the average values of FL1.45and 0.96 which occurs in both sides of embankment toes in Case 3.

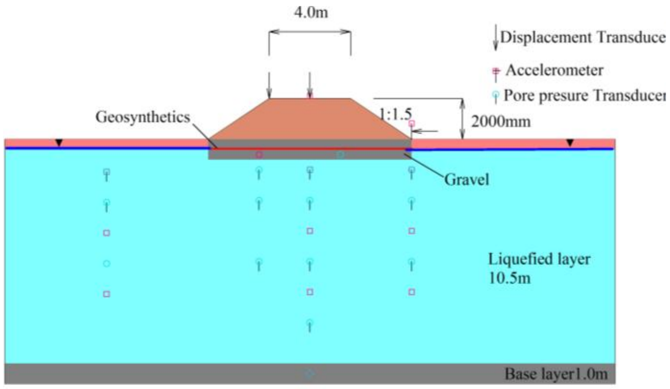


Figure 7. Schematic diagram of SECURE-G

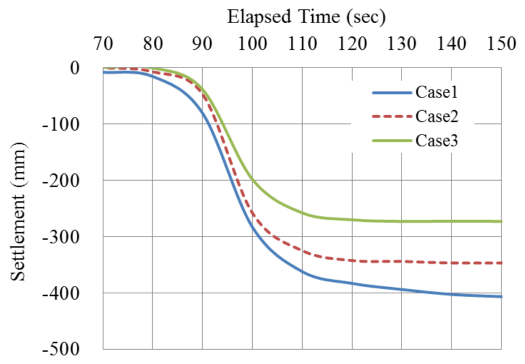


Figure 8. Time history of settlement of embankment shoulder

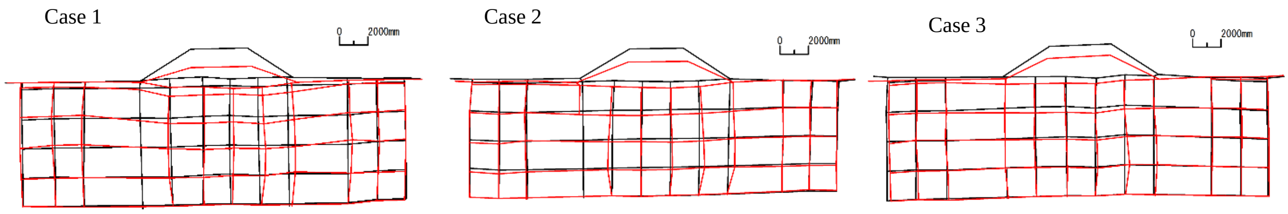


Figure 9. Ground deformation diagram after excitation

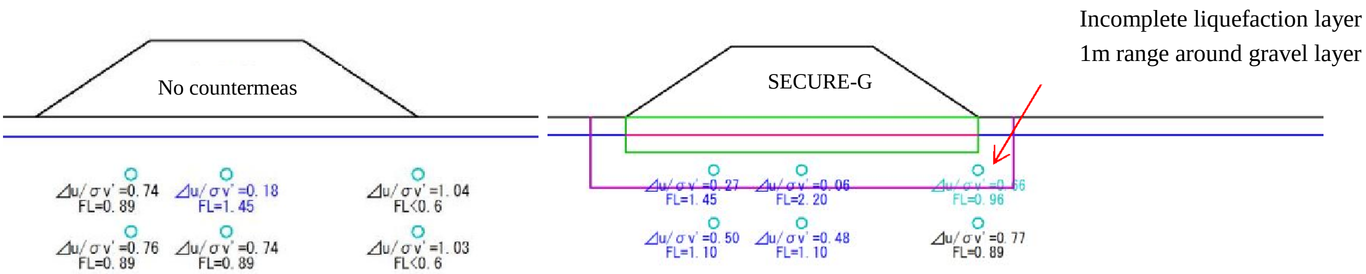


Figure 10. Distribution of excess pore water pressure ratio and Liquefaction resistance value (FL)

3 FEM DESIGN FOR CASE STUDY

3.1 *FEM design method*

ALID [4)] is used as a static FEM considering the influence of liquefaction in design. The static FEM (ALID) treats the mechanism of the flow phenomenon caused by liquefaction of the ground as a disappearance of rigidity due to the soil structure breakdown in the liquefaction layer. The technique of static FEM (ALID) is assumed to be deformed by a decrease in shear rigidity under self-weight of embankment.

As a design procedure, the value of liquefaction resistance (FL) is determined at first. Then, based on the result of liquefaction resistance (FL), it is classified into a region where rigidity decreases due to liquefaction and a region that does not liquefy. The stress state at point A in Figure 11 is defined by initial stress analysis. In case of liquefaction, it actually goes from point A to point C. However, it is assumed that it reaches point C via point B in this analysis. The stress-strain relationship of the liquefied element is represented by a downwardly convex bilinear model. As shown in Figure 12, the value of rigidity G1 of liquefied ground is defined by liquefaction intensity ratio RL and liquefaction resistance value FL.

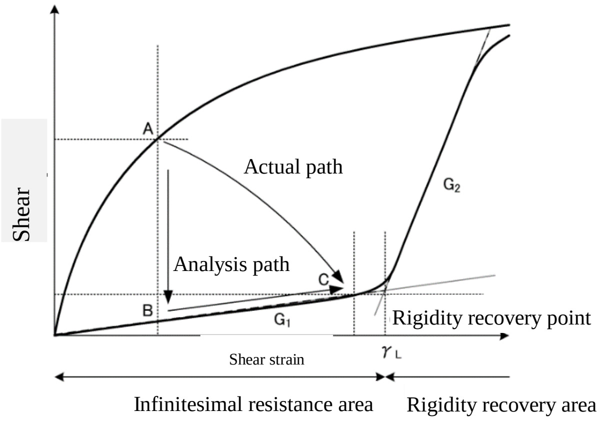


Figure 11. Stress-strain relation in ALID
(Yasuda et al., 1999)

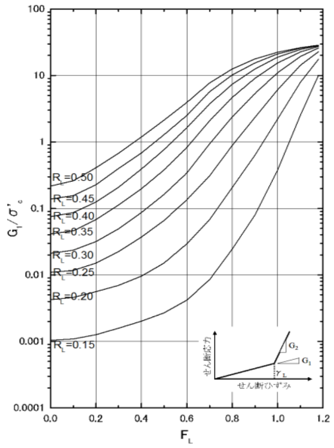


Figure 12. G1～FL～RL relation in ALID
(Yasuda et al., 1999)

3.2 *FEM design*

A plan view of the parking lot and its sectional view with SECURE-G are shown in Figure 13 and 14, respectively. As shown in Figure 14, the SECURE-G structure is installed at 1m depth of excavated ground. In another case, the SECURE-G structure is installed without excavation where underground pipes are being existed.

The update FEM analysis (ALID) was carried out after the completion of construction in order to confirm the deformation suppression effect of the embankment by SECURE-G. The simulated results of with and without countermeasure are describe.

Figure 15 shows the settlement of embankment crest, shoulder and horizontal displacement of embankment toe. In case of without countermeasure, the settlements of crest and shoulder are 30.6cm and 41.5cm, respectively. It is confirmed that the unequal settlement occurs in without countermeasure. In particular, as the settlement and displacement of the shoulder part hit the slide way, the emergency vehicle traffic is considered to be difficult. On the other hand, in case of countermeasures with SECURE-G, the unequal settlement and displacement was eliminated and the settlement of the shoulder was suppressed. According to this analysis result, it is considered that the SECURE-G is effective to suppress the deformation that allows emergency vehicles to be going out.

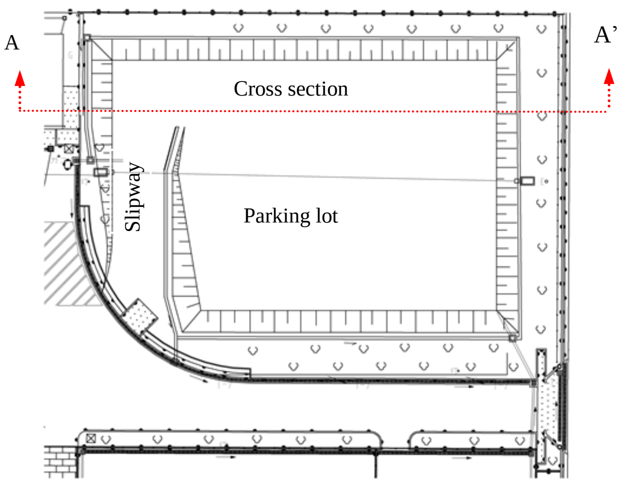


Figure 13. Plan view of parking lot

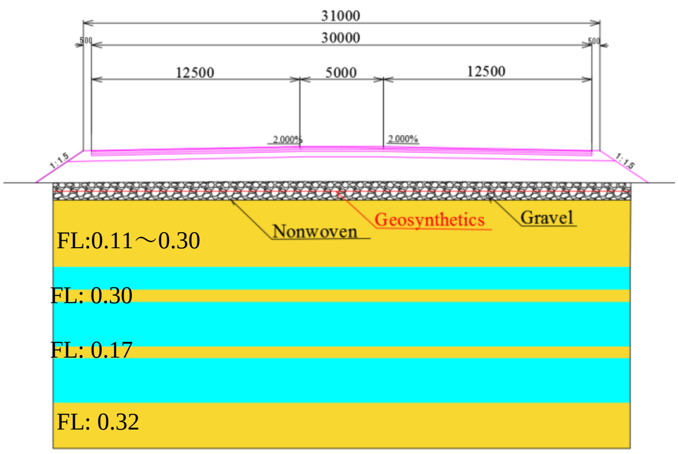


Figure 14. Sectional view with SECURE-G

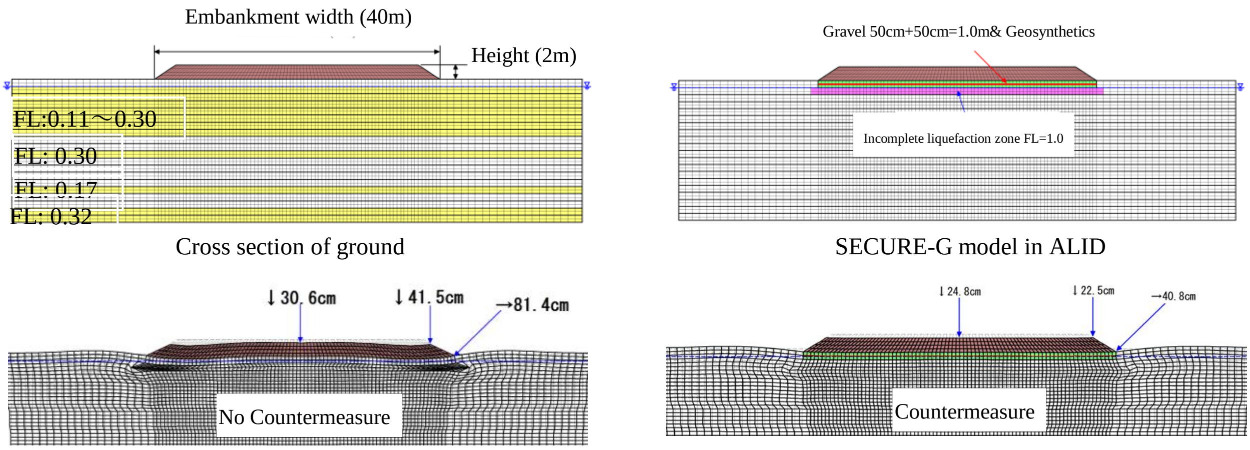


Figure 15. Analysis model and simulation results by ALID

4 CONSTRUCTION SITUATION

Two construction projects were implemented by contractors in 2013 and 2014. The construction situation is shown in Photo 1 and 2. The construction procedure is as follows.

1) Excavation: The ground was excavated to secure a space of thickness of gravel layer (1.0m) according to design requirement.

2) Installation of nonwoven: The nonwoven was laid at the bottom of the excavated area to prevent fine grain material does not flow into the gravel layer.

3) Filling gravel with leveling and compaction (lower portion): The complete thickness of the gravel layer is based on 25 cm. The desired thickness and flatness was secured by leveling. As compaction has a great influence on the stability and durability of the SECURE-G method, a compaction degree of 90% or more was secured by a tire rolling machine.

4) Geosynthetics spreading: The geosynthetics spreading should ensure the desire length for reinforcement. After spreading the reinforcing material, it is fixed with a fixing pin to prevent bending or sagging.

5) Filling gravel with leveling and compaction (upper portion): The upper portion of 50cm thickness of gravel layer is filled. The desired thickness and flatness was secured by leveling. As compaction has a great influence on the stability and durability of the SECURE-G method, a compaction degree of 90% or more was secured by a tire rolling machine. Careful attention was paid to prevent the damage of geosynthetics by without running the heavy equipment on the geosynthetics in directly.

6) Embankment: The embankment above the structure of SECURE-G was constructed by a prescribed management method based on compliance provisions of NEXCO Earthwork Management and Management Procedure.

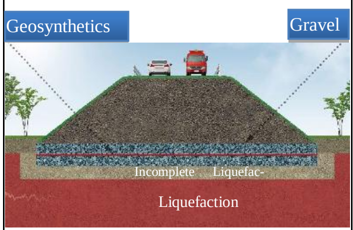
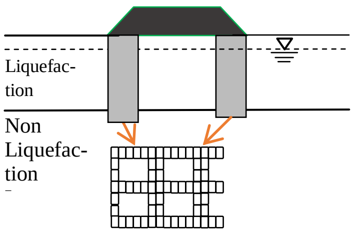
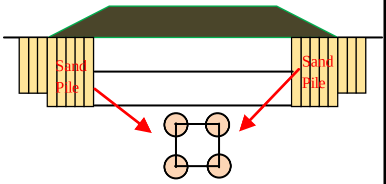
Photo 1. Compaction status of gravel layer

Photo 2. Installation status of geosynthetics

5 CONCLUSION

1) By adopting the SECURE-G method, a significant cost reduction could be achieved compared with the other ground improvement which is generally considered as a liquefaction countermeasure. In terms of workability by SECURE-G, heavy machineries used for ground improvements are not required and easy to install. The superiority of SECURE-G method is shown in Table 1 compared with the other methods.
2) Liquefaction of the ground has been strongly recognized all over the world due to damage of building collapse caused by the Niigata earthquake in 1964. In addition, according to the Hyogo Ken Nanbu Earthquake in 1995 and the Tohoko Region Pacific Offshore Earthquake in 2011, it is necessary to develop the design method for large earthquake. The performance design has been introduced at the present. Regarding embankment, seismic resistance at the time of large-scale earthquakes has been required in which the design law has been reviewed with increasing of knowledge of disaster prevention such as securing emergency transportation routes.
3) In the reality, it is impossible to adopt the conventional ground improvement as the cost is significantly high. In the movement of performance design, FEM is introduced to investigate the deformation which allows without leading destruction and easy to repair.
4) A simple liquefaction countermeasure of SECURE-G method using geosynthetics sandwiched with gravels is developed and it can be handled with limited business cost. In the future, we are planning to increase execution records according to the needs to reduce settlement and suppress lateral displacement.

Table 1. Comparison on SECURE-G and other ground Improvement methods

Comparison (Proposal)	SECURE-G	Deep Mixing	Sand Compaction Pile
Concept			
Construction	• Allows liquefaction but suppresses deformation • Install entire surface under embankment base	Prevent liquefaction by solidification Improvement by grid shape at near embankment toes	Prevent liquefaction by compaction with sand piles Install at embankment toe or entire under embankment
Workability	No need specialist Local contractor is possible to construct.	Need specialist to construct	Need specialist to construct
Groundwater environment	Ensure permeability	Prevention of groundwater flow might occur.	Groundwater might be mudded.
Surrounding environment	Less surrounding influence during construction	Ground Contamination should be checked.	Surrounding ground deformation might occur.
Cost (approximation)	8～10 Thousand Yen/m^2 (2m gravel layer)	70～100 Thousand Yen/m^3	70～85 Thousand yen/pile (Φ:700mm ,L:10m)

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