Seismic Reinforcement for Foundation Utilizing Sheet Piles and Soil Improvement

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ABSTRACT

This paper reports a case study of seismic reinforcement for pile foundation of Daisokugawa Bridge in Kagawa prefecture in Shikoku Island. The most popular reinforcement method for the foundation is the additional pile method; however, it was difficult to adopt this method for Daisokugawa Bridge because some piers were close to the road. Therefore, we considered the possibility of adopting a reinforcement method utilizing sheet piles that can minimize the area widening of the footing. In conducting the design, it was necessary to verify that the shear failure would not occur during the Level 2 earthquake motion by executing a beam-spring analysis. As a result of the design calculation, this reinforcement method couldn't prevent the shear failure of the piles and the footing because the superstructure's inertial force is large and the liquefaction may occur during the earthquake. In consideration of these circumstances, we adopted a reinforcement method utilizing sheet piles and soil improvement: improving soil inside the steel sheet piles by the high-pressure injection stirring construction method. Already, installation of the steel sheet piles, the soil improvement and the expansion of the footing of two piers have been finished.

Key words: *seismic reinforcement, foundation, steel sheet pile, soil improvement, desing*

1. Outline of the project

1.1. Introduction

Since Japan may be hit by large earthquakes in the near future, seismic reinforcement for structures has been carried out all over Japan these days. Shikoku Railway Company has been carrying out seismic reinforcement of railway structures (Kagawa, 2016) based on "the ordinance of the ministerial concerning seismic reinforcement of designated railway facilities (Land, Infrastructure, Transport and Tourism, 2013)" (enforced since April 1, 2013). The sections below are subject to this seismic reinforcement project: the railway sections between Kojima and Utazu on the Honshi-Bisan Line, between Takamatsu and Tadotsu on the Yosan Line (**Fig. 1**), and over-road bridges and viaducts intersecting or running side by side with roads designated as emergency transport roads by municipalities.

This paper reports the seismic design and the construction for the seismic reinforcement of foundation structures of Daisokugawa Bridge in the Honshi-Bisan Line which is the most important railway line in Shikoku Railway Company.

1.2. Outline of Daisokugawa Bridge

Figs. 2 and 3 show the view of Daisokugawa Bridge. Daisokugawa Bridge is separated into two bridges for the outbound and inbound lines. Each bridge consists of a four-span continuous prestressed concrete box girder and five reinforced concrete piers and cast-in-place concrete piles. Furthermore, the pier heights for the outbound lines are ranged from a minimum of 19.75 m to a maximum of 22.80 m. On the other hand, the pier heights for the inbound lines are ranged from a minimum of 8.95 m to a maximum of 15.35 m.

The result of simplified seismic diagnosis showed that these bridges needed seismic reinforcement, however, it was difficult to carry out seismic reinforcement for this pier from the perspective of the workability, cost and construction period because the middle pier was constructed in the river. Therefore, we considered the possibility to make the seismic reinforcement for the middle pier unnecessary by apportioning the inertial force of the middle pier among the other piers on the land. We carried out a dynamic analysis of the bridge using a three-dimensional beam-spring model (**Fig. 4**). The input seismic wave was earthquake motion waves based on the hypothesis that the earthquake occurred somewhere along the Nankai Trough, the Median Tectonic Line or the hidden faults. The results of the dynamic analysis showed that if we carried out the seismic reinforcement for the piers on the land to increase the superstructure’s inertial force affecting the piers on the land, it would turn out to be unnecessary to carry out the seismic reinforcement for the middle one (**Fig. 5**). However, since the superstructure’s inertial forces affecting the piers on the

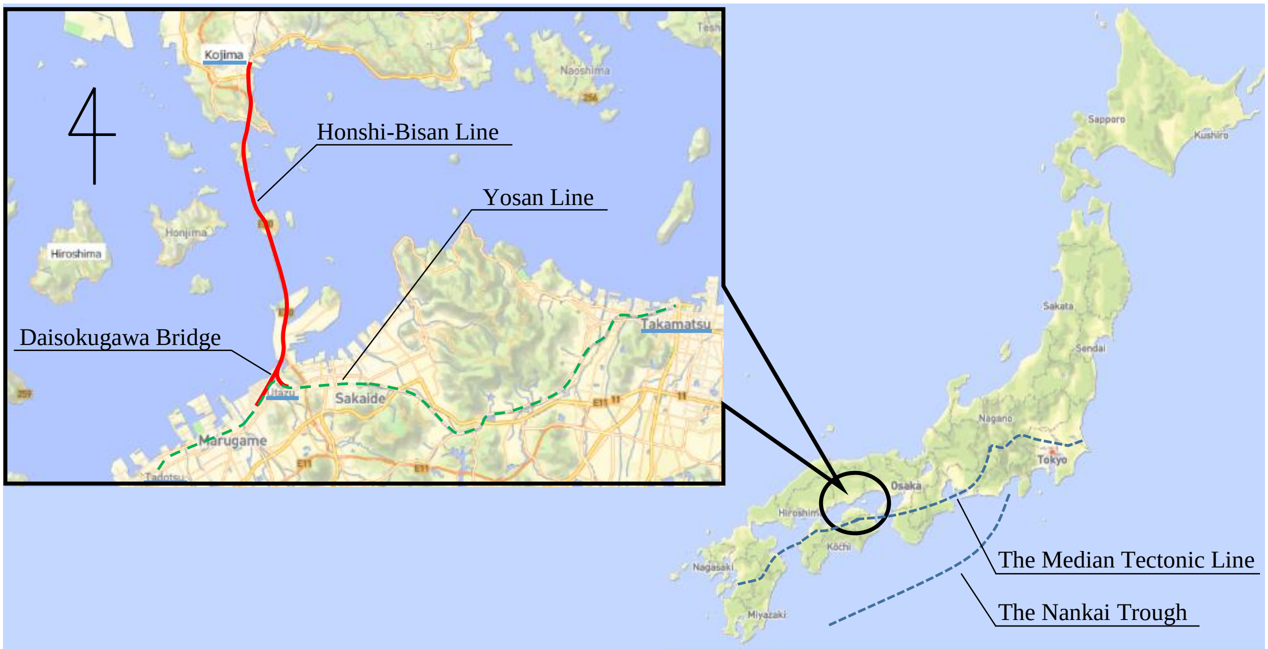


Fig. 1 Map of Honshi-Bisan Line and Yosan Line

Fig. 2 Full view of Daisokugawa Bridge

land increase, the seismic diagnosis showed the risk of the shear failure of pier bodies and piles and the failure of bearings.

Therefore, we decided to carry out the seismic reinforcement with carbon fiber sheets for pier bodies and restrainers for bearings. Additionally, since the burden of the foundation on the land will increase and these bridges are long-span bridges, we decided to carry out the seismic reinforcement for the foundation in consideration of restorability (Supervised by Railway Bureau, Ministry of Land, Infrastructure, Transport and Tourism, edited by Railway Technical Research Institute, 2012). Even though the most popular reinforcement method for the foundation is the additional pile method, it was difficult to adopt this method because some piers (2P, 4P, and 5P) were close to roads. Therefore, we considered the possibility to adopt a reinforcement method utilizing steel sheet piles (hereinafter called "sheet pile reinforce method") which can minimize the widening of the footing.

2. Outline of the sheet pile reinforce method

The sheet pile reinforce method is a seismic reinforcement method for improving the seismic performance of the foundation structure by installing steel sheet piles into the ground around the footing and connecting the steel sheet pile to the footing (**Fig. 6**). The specifications of the method such as the steel sheet pile length should be decided by design calculations, and the embedded depths are relatively short (about the same as the footing width) under general conditions. Therefore, this method is superior in terms of workability. Since the additional footing dimension can be reduced (up to about 1m), it is suitable for use at locations where land usage is severely restricted. Some studies have been carried out based on the model experiments, the numerical analysis, and so on. Furthermore, the design and construction manual has been prepared (Supervised by Railway Bureau, Ministry of Land, Infrastructure, Transport and Tourism,

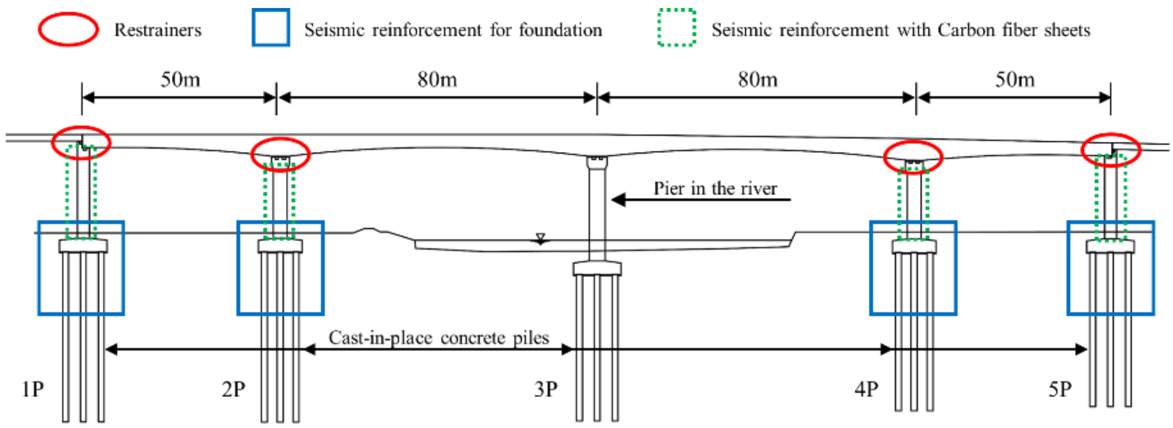


Fig. 3 Side view of Daisokugawa Bridge

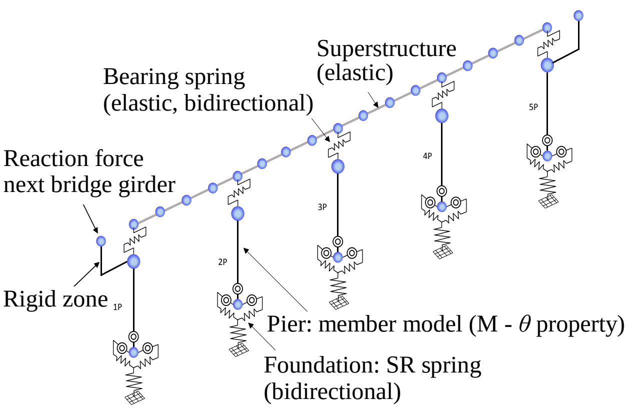


Fig. 4 Overall system frame analysis

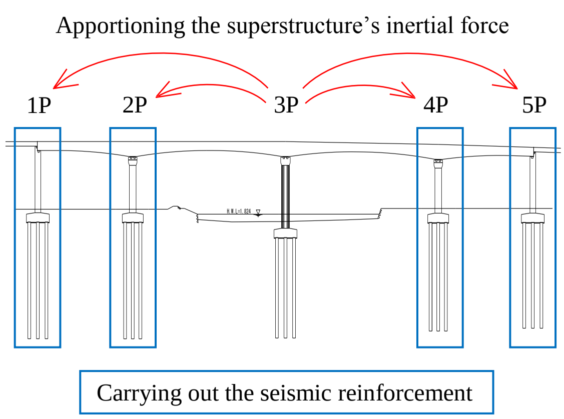


Fig. 5 Design concept of apportioning the superstructure's inertial force

edited by Railway Technical Research Institute, 2012) based on the knowledge obtained from these studies.

Since this method is not a large-scale reinforcement, it has often been used in the cases where ground conditions are relatively good until now. However, some studies have also been conducted regarding the reinforcement effects on pile foundations located in the soft ground and the liquefiable ground in recent years. Sanagawa, *et al*. prepared a one-sixth model of the pile foundation, and they conducted the experiment on the seismic performance of the sheet pile reinforce method on liquefiable ground (Sanagawa, *et al.*, 2017). This experiment was conducted under two different kinds of conditions by changing the specifications of the structure and input waves: one was a case where it was mainly influenced by the ground deformation, and the other was a case where it was mainly influenced by the inertial force. Additionally, the steel sheet pile was embedded in the non-liquefiable layer in both conditions.

As a result of this experiment, in the former case, the displacement of the model structure of the pile foundation was smaller than the sheet pile reinforce method. As a result, it was assumed that the ground flew between the piles because the resistance area (projected area of the horizontal direction) of the pile was small. Furthermore, it was given as one of the reasons that the steel sheet pile was received the ground deformation directly because the resistance area of the steel sheet pile was large.

On the other hand, in the latter case, the displacement of the model structure of the sheet pile reinforce method was smaller than the pile foundation. As a result, it was assumed that the vertical resistance of the steel sheet pile suppressed the rotation of the structure.

In the case of Daisokugawa Bridge, since this bridge was on the liquefiable ground and the superstructure's inertial force was strong, we assumed that this bridge corresponds to the latter case. For this reason, we considered whether the sheet pile reinforce method can be adopted or not for the seismic reinforcement based on the knowledge obtained from the abovementioned experiments.

3. Outline of the seismic design

The following is the outline of the seismic design. We compared the additional pile method for cast-in-place concrete piles with the sheet pile reinforce method in terms of costs and space required at the period of construction. In conducting the design calculation, we decided that the required performance was safe against the Level 2 earthquake motion (Supervised by Railway Bureau, Ministry of Land, Infrastructure, Transport and Tourism, Edited by Railway Technical Research Institute, 2012): verification about the vertical load and the tensile load at the pile head, the maximum response horizontal displacement at top of the footing, the maximum response angle of rotation at the top of the footing, the failure of members (the pier body, the footing and the pile).

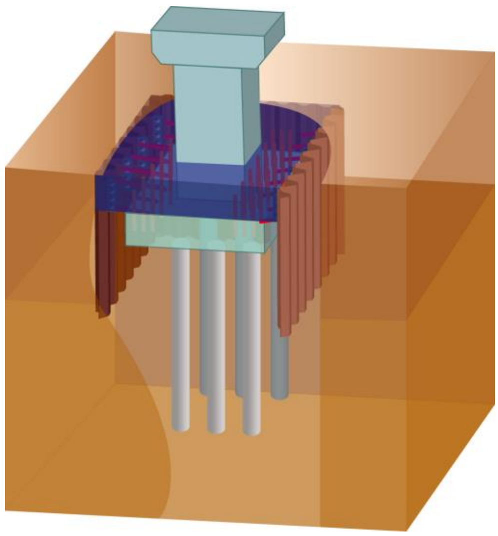


Fig. 6 Sheet pile reinforce method

The design calculations were conducted according to the design standards for railway structures (Supervised by Railway Bureau, Ministry of Land, Infrastructure, Transport and Tourism, Edited by Railway Technical Research Institute, 2012) and the design/construction manual of sheet pile reinforce method (Railway Technical Research Institute, Obayashi Corporation, Nippon Steel and Sumitomo Metal Corporation, 2016). In particular, the response value was calculated from the nonlinear static analysis using the beam-spring model and from the nonlinear response spectrum method (Supervised by Railway Bureau, Ministry of Land, Infrastructure, Transport and Tourism, Edited by Railway Technical Research Institute, 2012). The results of the design calculations showed that the general sheet pile reinforce method could not prevent the shear failure of the piles and the footing. As a result, it was assumed that the superstructure's inertial force was too strong and the suppressing effect of the rotation of the structure by the steel sheet pile was not enough when the liquefaction occurs. To ensure the applicability of the method to the liquefiable ground, we considered the possibility of adopting a reinforcement method utilizing sheet piles and soil improvement (Shioi, *et al.*, 2004): the sheet pile reinforce method together with improving soil inside the steel sheet piles by the high-pressure injection stirring construction method. In conducting the design calculation, we verified that the shear failure at the pier body, the footing, the pile, and the improved soil would not occur during the Level 2 earthquake motion by executing the beam-spring analysis and the FEM analysis.

Table 1 and Fig. 7 show the seismic reinforcement method adopted for the foundation. For a pier 1P, which was not close to the road, the additional pile method was adopted for cost reasons. For piers 2P and 4P with strong superstructure's inertial force, utilizing sheet piles and soil improvement was adopted because the large-scale reinforcement was required if the additional pile method was applied, and because the piers were close to the road.

Table 1. Results of comparative study

pier	Adopted method	Grounds for adoption
1P (in/outbound lines)	Additional pile method	Cost
2P (in/outbound lines)	Utilizing Sheet Piles and Soil Improvement	Cost
4P (in/outbound lines)	Utilizing Sheet Piles and Soil Improvement	Occupation of road space and cost
5P (in/outbound lines)	Utilizing Sheet Piles and Soil Improvement	Cost

For a pier 5P, it was found that the distance between the pier for the inbound line and that for the outbound line was very short and piles could only be installed in the direction to expand the footing in parallel with the line even if the additional pile method was applied. In this case, because the scale of the seismic reinforcement would be extremely large, utilizing sheet piles and soil improvement was adopted for cost reasons. **Figs. 8 and 9** show the drawing of pier 1P and 2P. As can be seen from these figures, if the additional pile method is applied, it is necessary to expand the footing. As a result, it is considered that the large

Table 2. Construction process

step	Additional pile method	Utilizing sheet piles and soil improvement
1	Placing cast-in-place concrete piles	Installing steel sheet piles
2	Primary excavation	Primary excavation
3	Installing steel sheet piles for earth retaining	Soil improvement
4	Secondary excavation	Executing shore strut and waling
5	Pile head treatment	Secondary excavation
6	Driving anchors	Driving anchors
7	Assembling reinforcing bars	Assembling reinforcing bars
8	Placing expanded footing	Placing expanded footing
9	Primary backfilling	Backfilling
10	Pulling out steel sheet piles	
11	Secondary backfilling	

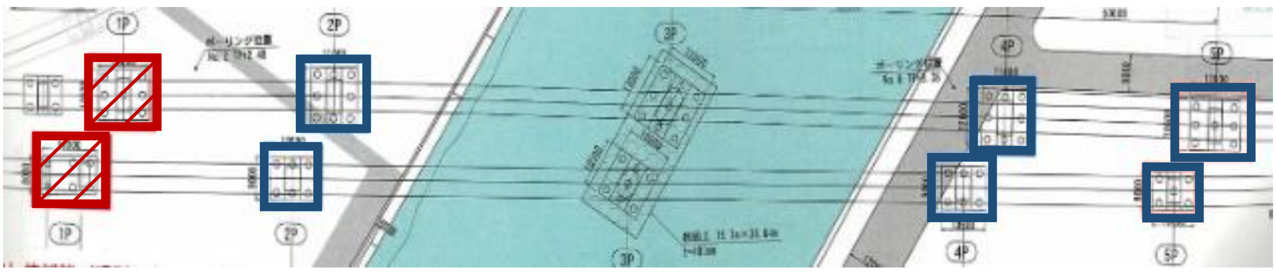


Fig. 7 Adopted seismic reinforcement for foundation
(Hatching：Additional pile method, Not hatching：Utilizing Sheet Piles and Soil Improvement)

horizontal force is exerted on the footing by the lateral flow when the liquefaction occurs.

4. Construction

4.1. Outline

Table 2 shows the construction process under both methods: the additional pile method and utilizing sheet piles and soil improvement. Regarding the construction under the additional pile method, because there was an approximately 15m-thick sandy gravel layer in the ground (**Fig. 10**), the cast-in-place concrete piles were adopted by the full rotation all-caisson method, which can be applied to the hard ground and can reliably prevent excavation wall collapse. Regarding the construction utilizing sheet piles and soil improvement, we adopted the hat-shaped steel sheet plies which have high joint efficiency and can be applied at low cost.

4.2. State of construction

Photos 1, 2, and 3 show construction conditions for the installation of the steel sheet piles at pier 2P. At present, piles are placed at six locations in all at the pier 1P of the outbound line, while at ten locations in all at the pier 1P of the inbound line. At pier 2P, the installation of the steel sheet pile, the soil improvement, and the expansion of the

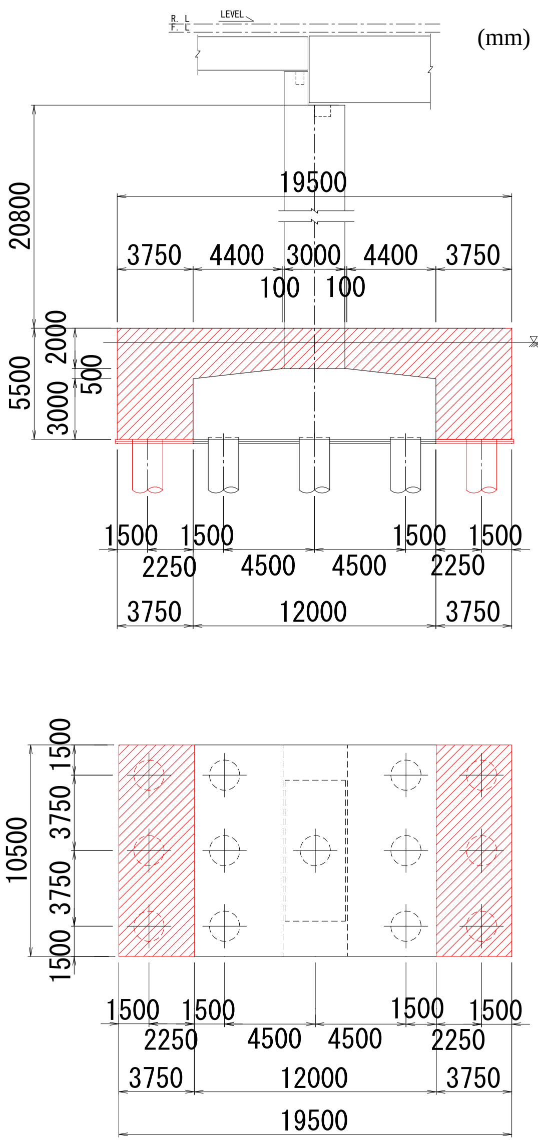


Fig. 8 Drawings of the additional pile (1P)

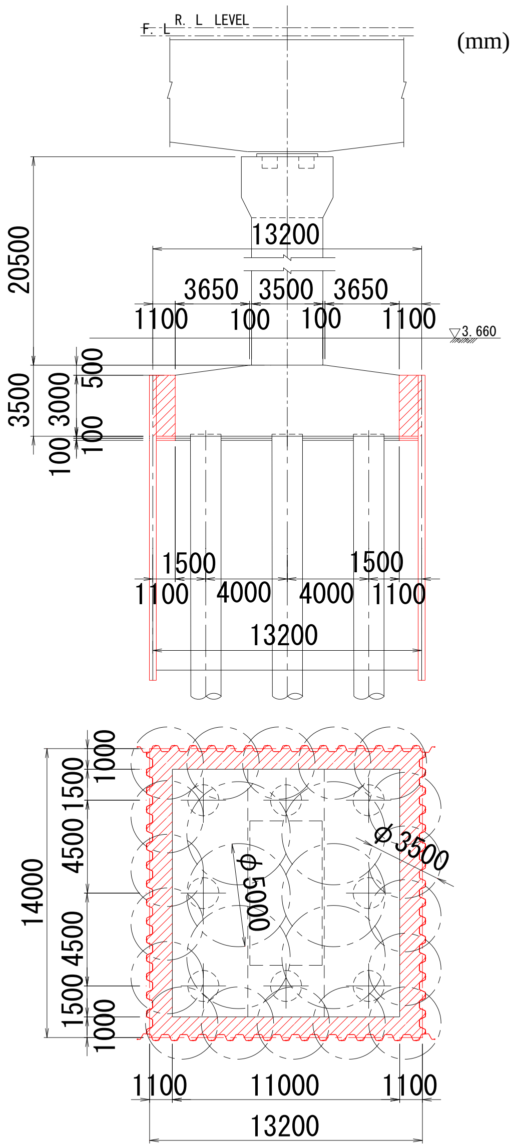
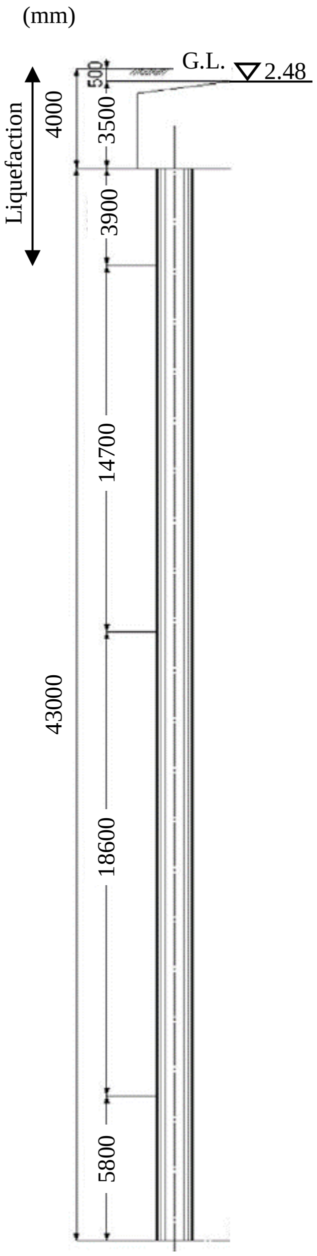


Fig. 9 Drawings of the utilizing sheet piles and soil improvement (2P)

footing have been finished for the inbound and outbound lines. Regarding the installation of the steel sheet piles, it was conducted using “the silent piler (Tauchi, 1999) (Official Website of GIKEN LTD.)” that can be applicable to press-in with augering. At pier 4P and pier 5P, installation of the steel sheet pile has been finished for the inbound and outbound lines and preparations are being made for the soil improvement.



Ground classification	N-values for design
Backfilling soil	-
Sandy soil	9
Sandy gravel layer	29
Sandy soil	37
Cohesive soil	34
Cohesive soil	50

Fig. 10 Geological condition

Photo 1. View of installing steel sheet piles (outbound 2P)

Photo 2. View of the installed steel sheet piles (inbound 2P)

Photo 3. View of the soil improvement (outbound 2P)

Regarding the construction for the outbound line, it has been done under a sufficient construction space because the overhead clearance is about 20 m under the girders for the outbound line. By contrast, the construction for the inbound line has been done under harsh overhead clearance restrictions because the overhead clearance ranged from a minimum of 7 m to a maximum of 14 m. Therefore, the piles and steel sheet piles were installed using machines available under the low overhead clearance, and the work was done more carefully to prevent the machines from hitting the girders. Furthermore, the displacement of the piers has been measured by total station at any time during the construction because this reinforcement work has been carried out for existing railway lines in operation.

5. Conclusions

This paper describes the design and construction of seismic reinforcement for Daisokugawa Bridge. Since some piers were close to the road, we considered the possibility of adopting a reinforcement method utilizing sheet piles that can minimize the area widening of the footing. In particular, the response value was calculated from the nonlinear static analysis using the beam-spring model and from the nonlinear response spectrum method As a result of the design calculation, the general sheet pile reinforce method could not prevent the shear failure of the piles and the footing presumably because the superstructure's inertial force is large and the liquefaction may occur during the earthquake.

In consideration of these circumstances, we adopted a reinforcement method utilizing sheet piles and soil improvement to apply the liquefiable ground. Already, installation of the steel sheet piles, the soil improvement and the expansion of the footing of two piers have been finished. In the near future, the expansion of the footing at pier 1P and the soil improvement work at piers 4P and 5P will be executed. Therefore, we intend to proceed with this project with due full consideration for safety.

References

Kagawa, K. 2016. Seismic Reinforcement by Shikoku Railway Company, in *The Journal of Japan Railway Civil Engineering Association*, Vol. 54, Japan Railway Civil Engineering Association. (in Japanese)

Ministerial of Land, Infrastructure, Transport and Tourism. 2013. The Ordinance of The Ministerial Concerning Seismic Reinforcement of Designated Railway Facilities, The Ordinance of the Ministerial of Land, Infrastructure, Transport and Tourism, No. 16, Date of last access March 23, 2018, http://elaws.e-gov.go.jp/search/elawsSearch/elaws_search/lsg0500/detail?lawId=425M60000800016. (in Japanese)

Official Website of GIKEN LTD. Silent Piler/The Latest Models. Date of last access March 23, 2018, https://www.giken.com/en/products/silent_piler/.

Supervised by Railway Bureau. 2012. Ministry of Land, Infrastructure, Transport and Tourism, Edited by Railway Technical Research Institute, The Design Standards for Railway Structures and Commentary (Seismic Design), Maruzen Publishing Co. Ltd. (in Japanese)

Supervised by Railway Bureau. 2012. Ministry of Land, Infrastructure, Transport and Tourism, Edited by Railway Technical Research Institute, The Design Standards for Railway Structures and Commentary (Foundation Structures), Maruzen Publishing Co. Ltd. (in Japanese)

Railway Technical Research Institute, Obayashi Corporation, Nippon Steel and Sumitomo Metal Corporation. 2016. Design and Construction Manual (Draft) of Seismic Reinforcement Method for Existing Railway Foundation Structure Using Steel Sheet Piles (Sheet Pile Reinforce Method), Third edition. (in Japanese)

Sanagawa T., Nishioka H., Matsuura K., Higuchi S., Toda K., Taenaka, S. 2017. Experimental and Numerical Study on Seismic Behavior of Pile Foundations Utilizing Sheet Pile Reinforcement in Liquefied Ground. Japanese Geotechnical Journal, Vol. 12, No. 2, pp. 197-210. (in Japanese)

Shioi Y., Segawa N., Inagawa K., Kato K. 2004. Development of Seismic Reinforcement Method Utilizing Soil Improvement for Pile Foundation. Proceedings of the 7th symposium on ductility design method for bridges. (in Japanese)

Tauchi H. 1999. Silent Piler and Press-in Method (Press-in Construction Technology Originated in Hydraulic Pressure). Hydraulics & Pneumatics, Vol. 38, No. 3, pp. 9-14, Japan Industrial Publishing Co. Ltd. (in Japanese)