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Design calculation method for sheet pile reinforcement method in liquefiable ground

K. Kasahara, T. Sanagawa & M. Koda
Railway Technical Research Institute, Kokubunji, Tokyo, Japan

ABSTRACT: A reinforcement method utilizing steel sheet piles (sheet pile reinforcement method) is sometimes adopted in Japan for reinforcing existing foundation structures. This is a reinforcement method where steel sheet piles are installed into the ground so as to surround the existing footing and are integrated with the footing. Since the widening width of the footing can be minimized, this reinforcement method is often adopted at locations where land usage is severely restricted. However, it hasn't been clarified whether this reinforcement method can be applied to structures in the liquefiable ground. Therefore, in this study, model vibration experiments are conducted to clarify the effect and the mechanism of this reinforcement method for pile foundation structures in the liquefiable ground. Furthermore, considering of the experimental results, a structural analysis method is proposed to design this reinforcement method, which can correspond to changes in strength and stiffness of the ground due to liquefaction.

1 INTRODUCTION

When the liquefaction occurs during an earthquake, the ground suddenly loses strength and rigidity, causing great damage to the foundation structures of bridge piers and viaducts. As a result, the structural members of the foundation might be damaged or the bridge might collapse. For example, in the 1995 Hyogo-ken Nanbu Earthquake, many pile foundation structures were damaged due to liquefaction. Subsequent investigations and researches clarified that the damage of pile foundation structures was not only caused by the inertial force acting on the superstructure, but also by the increase in the ground displacement due to liquefaction. With the background of such disaster cases, the foundation structures are designed considering the effect of the liquefaction in the current design standards. However, not a few older structures have to implement liquefaction countermeasures because in these structures the effect of the liquefaction was not considered in the design stage.

As conventional liquefaction countermeasures for existing pile foundation structures, there are enumerated ones by additional piles (Kishimoto et al. 1998) and by soil improvement (Kiryu and Sawada. 2005). However, as the additional pile method requires a large expansion of the land usage and the reinforcement work becomes large-scale, resulting in high cost. Furthermore, the construction is often difficult in urban areas where there are many adjacent structures under bridge girders. On the other hand, the soil improvement may not be applicable to structures in rivers due to environmental considerations. For this reason, it is expected to develop a liquefaction countermeasure method that is excellent in economic efficiency as well as workability for foundation structures in narrow areas and under harsh overhead clearance restrictions.

Incidentally, a reinforcement method is proposed, which utilizes steel sheet piles (hereinafter called "sheet pile reinforcement method") (Nishioka et al. 2010) (Figure 1). This is a reinforcement method where steel sheet piles are installed into the ground so as to surround the existing footing and are integrated with the footing. This reinforcement method mainly targets existing pile foundations of relatively small and medium-sized, where footing width is about 5 to 10 m. Although the specifications such as the steel sheet piles length are decided by design calculations, the embedded depths are relatively short (about the same length as the footing width) under general conditions. Therefore, this reinforcement method is superior in that it doesn't require a large pile driving machine. Since the widening width of the footing can be minimized, this reinforcement method with excellent economic efficiency and workability has been often adopted. However, it hasn't been clarified whether this reinforcement method can be applied to structures in the liquefiable ground. If the effect of this reinforcement method on the liquefiable ground can be confirmed, it can be a reinforcement method with excellent economic efficiency and workability on the liquefiable ground.

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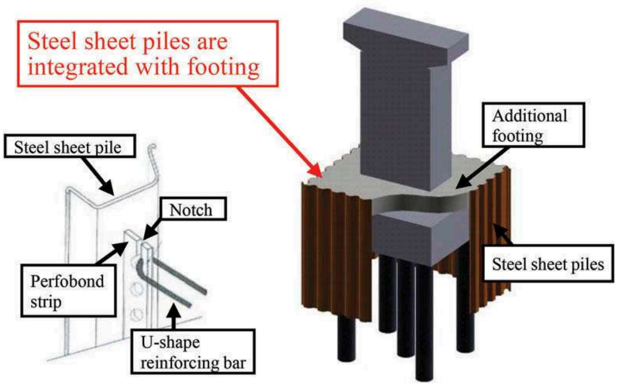


Figure 1. Sheet pile reinforcement method (Sanagawa et al. 2015).

Therefore, in this study, model vibration experiments are conducted to clarify the effect and the mechanism of the sheet pile reinforcement method for pile foundation structures in the liquefiable ground. Furthermore, considering the experimental results, a structural analysis method is proposed to design this reinforcement method, which can correspond to changes in strength and rigidity of the ground due to liquefaction.

2 CONFIRMATION OF REINFORCEMENT EFFECT BY MODEL EXPERIMENT (SANAGAWA ET AL. 2015)

At first, we conduct a model vibration experiment to clarify the reinforcement effect of the sheet pile reinforcement method on the liquefiable ground. Figure 2 shows an outline of the model. The prototype of the target structure is a pile foundation pier, where body height: 6.0 m, yield seismic intensity: 0.586, equivalent natural period: T_{eq} = 1.34 sec, ground natural period: T_g = 1.95 sec. The foundation type is a driving pile with a pile length of 15.0 m using PHC piles (the diameter is 500 mm, and the number of piles is 2 × 2). We assume 25H type hat-shaped steel sheet piles for reinforcement, and the pile base is driven into the non-liquefiable layer. We perform the vibration experiments with a 1/6 scale model of the prototype, setting the specifications according to the similarity laws (Kagawa. 1988) (Table 1). The pile model is a square steel pipe with dimensions of 50 mm × 50 mm and a thickness of 1.6 mm, and the sheet piles model is a steel plate with a thickness of 4.5 mm. Regarding the sheet piles model, we confirm by pre-analysis that the axial force of the steel sheet pile is dominant as the mechanism for the sheet pile reinforcement method in the liquefiable ground. Therefore, the sheet pile model simulates the base machined steel sheet pile (Nakayama et al. 2007) with excellent vertical resistance. Specifically, we weld U-shaped steel plates (height: 33 mm, width: 88 mm) to the section with a base of 300 mm (Figure 3). Here, the base machined steel sheet pile is a steel sheet pile in which the closed cross-section is provided by

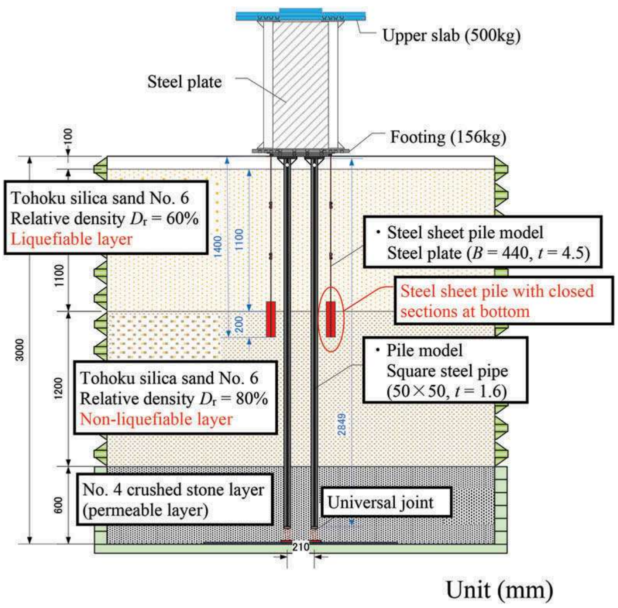
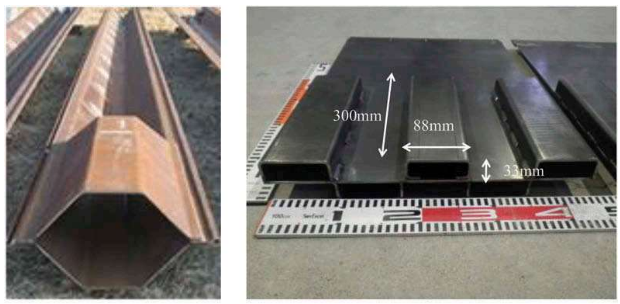


Figure 2. Overview of model experiment.

Table 1. List of similarity laws.

Items	Model (M)	Actual thing (A)	M/A	Target value
Height of column (mm)	1000	6000	0.167	$1/\lambda = 0.167$
Pile length (mm)	2849	15000	0.190	
βL (pile)	5.18	4.86	1.07	1.0
βL (steel sheet pile)	5.49	4.88	1.13	1.0
Natural frequency of the ground f_g (H_z)	7.35	1.95	3.77	$\lambda^{3/4} = 3.83$
Natural frequency of the structure f_s (H_z)	4.50※	1.34	3.35	

※ A case when inputting



(a) Actual pile (b) Model used in experiment

Figure 3. Steel sheet piles with closed sections at the bottom (Website of NIPPON STEEL CORPORATION. (date of last access is November 10, 2020).

combination processing to improve the vertical bearing capacity.

The model vibration experiment is carried out using the large vibration test device and the laminated shear soil tank owned by the Railway Technical Research Institute. The internal dimensions of the laminated shear soil tank are 3000 mm in width, 1100 mm in depth, and 3000 mm in height. The part which is 2400 mm deep from the top of the soil tank is composed of 12 stages of shear frames. Each shear frame is supported by a linear guide and can be deformed depending on the movement of the ground. A rubber membrane is installed inside the soil tank, and after installing the model inside of this, the model ground is constructed. The geo material is Tohoku silica sand No. 6, and it is saturated by injecting water from the bottom of the soil tank after construction. The vibration waveform is Level 2 seismic motion (spectrum I that models an earthquake of plate boundary type) at bedrock used in the design of railway structures (Ministry of Land, Infrastructure, Transport and Tourism. 2012. Seismic Design). We use this waveform with the time axis compressed according to the similarity laws (Figure=4). Table 2 shows a list of measurement items. We confirm the effect of the sheet pile reinforcement method for the ground conditions that have become completely liquefiable due to vibration (Figure 5).

Figure 6 shows the outline of the model vibration experiment results. We confirm that the maximum response rotation angle is reduced by about 30% and the maximum horizontal response displacement is reduced by about 5% at the upper slab by the sheet pile reinforcement method. Furthermore, the maximum shear force is suppressed by about 30% and the maximum axial force is reduced by about 20% at the pile head by the sheet pile reinforcement method. This is because the vertical resistance of the steel sheet pile suppresses the rotational behavior of the superstructure, and the stress generated at the pile head is reduced.

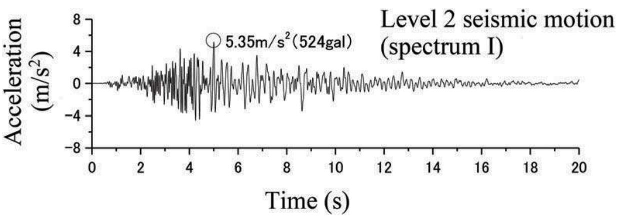


Figure 4. Time history data of input waves (in model scale).

Table 2. List of measurement items.

Items	Positions	Methods
Displacement	Upper slab, Footing, Ground surface, Soil (soil tank)	Displacement sensor
Acceleration	Upper slab, Footing, Ground	Accelerometer
Excess pore water pressure	Ground	Piezometer
Strain	Pile body, sheet pile	Strain gauge

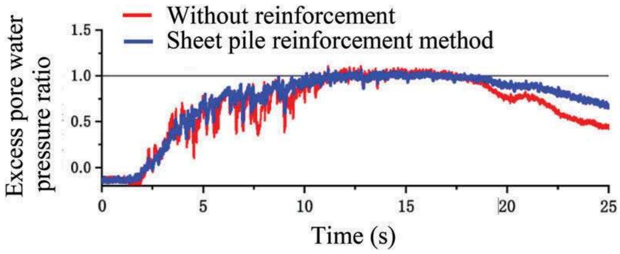


Figure 5. Time history data of excess pore water pressure ratio.

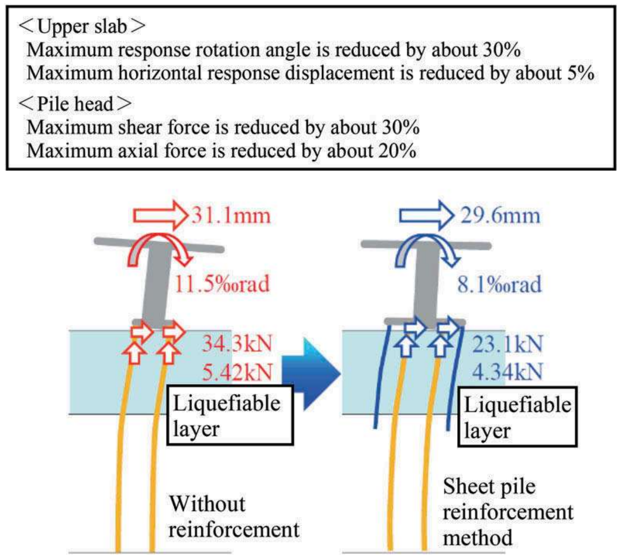


Figure 6. Effect of sheet pile reinforcement method.

3 VERIFICATION OF NUMERICAL ANALYSIS MODEL (SANAGAWA ET AL., 2015; TODA ET AL., 2016)

3.1 *Structural analysis model*

To evaluate the behavior of the pile foundations reinforced by the sheet pile reinforcement method during liquefaction, we perform numerical analysis using a two-dimensional beam spring model to verify the applicability of the model (Sanagawa et al. 2015, Toda et al. 2016). We used the model shown in Figure 7 in order to study the effect of ground displacement on the structure. This model connects the soil pillar model simulating the ground with piles and sheet piles by a horizontal ground spring. This model inputs the response displacement of the ground to the foundation through the ground spring. This makes it possible to directly consider the effects of interactions

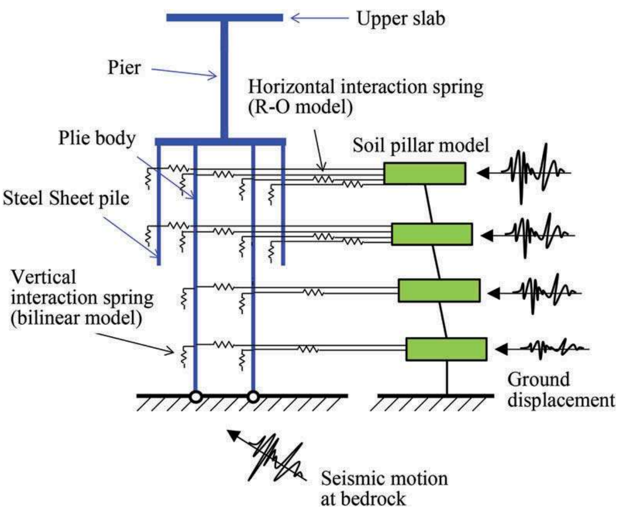


Figure 7. Overview of analytical model.

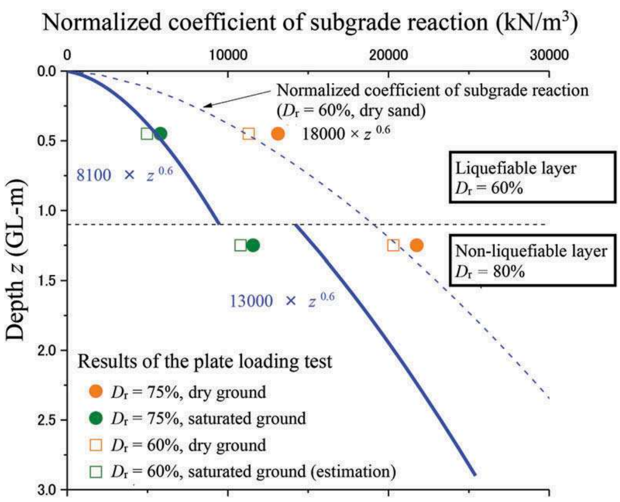


Figure 8. Modeling of normalized coefficient of subgrade reaction.

with structures in a dynamic analysis. In this analysis, we input the time history waveform of the ground displacement measured at each depth in the model vibration experiment into directly the soil pillar model.

3.2 *Horizontal interaction between pile and soil*

We set the horizontal interaction spring considering the displacement level dependency, the pile width dependency, and the decrease in rigidity due to the increase in excess pore water pressure.

(1) Normalized horizontal coefficient of subgrade reaction

Suzuki et al. (2009) conducted a horizontal flat plate loading experiment (φ= 300 mm) using a screw jack. They examined the subgrade reaction of the pile for dry ground (D_r = 60% & D_r = 75%) and for saturated ground (D_r = 75%). These experimental results show that the normalized horizontal coefficient of subgrade reaction is roughly proportional to the 0.6th power of depth. Therefore, we evaluate the coefficient of subgrade reaction by this power law (Figure 8). In addition, the initial shear stiffness G_0 at D_r = 80% obtained from the triaxial compression test was about 1.6 times the value of D_r = 60%. Thus, we also estimate the normalized coefficient of subgrade reaction by multiplying 0.6th power of the depth. The formula for calculating the normalized horizontal coefficient of subgrade reaction applying to the interaction spring model is shown below.

$$k_{hrB=300}(z) = 8100 \times z^{0.6} (0 \leq z \leq 1.1) \quad (1)$$

$$k_{hrB=300}(z) = 13000 \times z^{0.6} (1.1 \leq z \leq 2.3) \quad (2)$$

where z is the depth (m) from the ground surface, and $k_{hrB\ =\ 300}$ is the normalized horizontal coefficient of subgrade reaction when the loading displacement is 1% of the plate width.

(2) Size effect on horizontal coefficient of subgrade reaction

The width of the loading plate used in the above study differs from the width of the pile and sheet pile model in this vibration experiment. For this reason, we have to consider the influence of the size effect. Referring to the specifications for highway bridges (Japan Road Association 2012) and the design standard for railway structures (Ministry of Land, Infrastructure, Transport and Tourism 2012. Foundation Structures), we calculate the value of the normalized horizontal coefficient of subgrade reaction of the model pile and model sheet piles. Specifically, we used the relational expression that the normalized horizontal coefficient of subgrade reaction is -3/4 power of the pile width as shown in equation (3).

$$k_{hr}/k_{hrB=300} = (B/0.3)^{-3/4} \quad (3)$$

where B is the loading width (m). In this vibration experiment, the pile width is 0.050 m and the sheet pile width is 0.450 m.

(3) Displacement level dependency

Regarding the displacement level dependency, the R-O model (Jennings 1964) is applied. We calibrate the parameters of the R-O model for the displacement level dependency of the horizontal coefficient of subgrade reaction by using the result of the vibration generator and static horizontal loading test conducted on the dry ground of the same ground material (Figure 9). At this time, the normalized displacement is 1% of the pile width (0.050 m) and steel sheet piles width (0.450 m). In this analysis, the displacement level dependency of the horizontal coefficient of subgrade reaction changes from moment to moment by using the time history of the pile displacement.

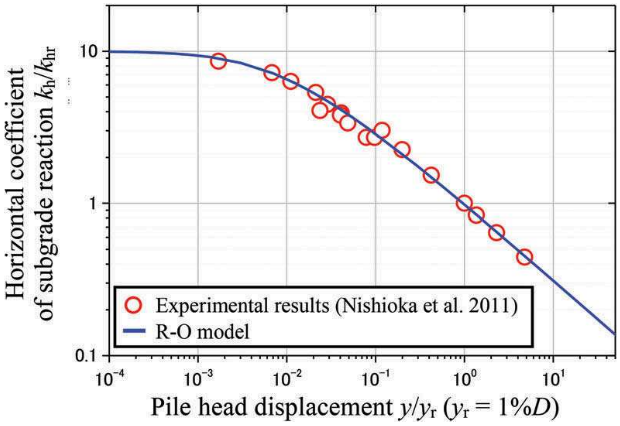


Figure 9. Modeling of displacement level dependency of horizontal coefficient of subgrade reaction.

(4) Reduction of coefficient of subgrade reaction due to liquefaction

During liquefaction, the coefficient of subgrade reaction reduces because the effective confining pressure decreases as the excess pore water pressure rises. Previous studies obtained the effect of the excess pore water pressure ratio on the coefficient of subgrade reaction from experiments (Sawada et al. 1998, Matsumoto et al. 1987, Yoshizawa et al. 2000, Kawai et al. 2001, Igarashi et al. 2003). Many of these studies reported that the coefficient of subgrade reaction decreases in proportion to the power of the water pressure ratio as shown in equation (4).

$$k_h \propto (1 - u)^{\alpha} \tag{4}$$

where u is the excess pore water pressure ratio. In this analysis, a low-pass filter (f_c = 1.0H_z) is applied to the time history waveform (Figure 5) of the excess pore water pressure ratio u obtained in the vibration experiment to remove the short-period component. In addition, the reduction rate of the coefficient of subgrade reaction due to the liquefaction is changed with time history by setting $\alpha = 0.5$.

3.3 *Vertical interaction between pile and soil*

For the vertical interaction spring of the piles, we apply a bilinear model based on the results of the separately conducted steel pipe pile (φ50 mm) push-in/pull-out test. Regarding the vertical soil spring of the steel sheet piles, we also apply a bilinear model based on the results of the steel sheet pile push-in test (Sanagawa et al. 2010) (Figure 10). The effect of liquefaction is assumed to be proportional to the power of the excess pore water pressure ratio (α = 0.5), similar to the horizontal interaction spring.

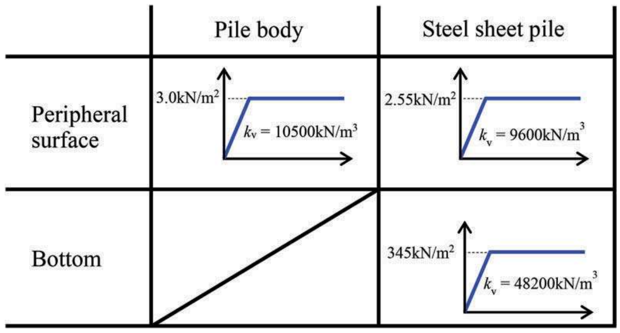


Figure 10. Modeling of vertical interaction springs.

3.4 *Modeling of members*

The structural members are modeled as a linear model because the stress of the members in the experiment did not exceed the yield point. The results of the bending test and axial compression test are applied to the pile body and the steel sheet pile. For the slab, column, and footing, the cross-sectional rigidity is calculated based on the dimensional specifications as Young's modulus is set to 2.05×10^8 (kN/m^2). Table 3 shows a list of cross-section specifications.

3.5 *Modeling of damping effect*

Typical examples of structural attenuation include structural damping, historical damping, and radiation damping. Since historical damping is considered in the non-linear model of the soil spring set in the previous section, Rayleigh damping is applied as another damping. From the results of a parametric study, we set $\alpha = 0.3$ and $\beta = 0.003$ so that the damping constants don't vary around the natural frequency of the structure to the natural frequency of the ground.

3.6 *Reproduction analysis of model experiment*

Using the analysis model constructed so far, we performed a reproduction analysis of the model experiment. As a result of the reproduction analysis, Figure 11 shows the time history waveform of the

Table 3. List of member specifications used in the analysis.

Structural member	Cross-sectional area (m^2)	Moment of inertia of area (m^4)
Upper slab	Rigid body	Rigid body
Pier body	Rigid body	Rigid body
Footing	Rigid body	Rigid body
Pile body	3.03×10^{-4}	1.05×10^{-7}
Steel sheet pile	6.55×10^{-4}	3.42×10^{-9}

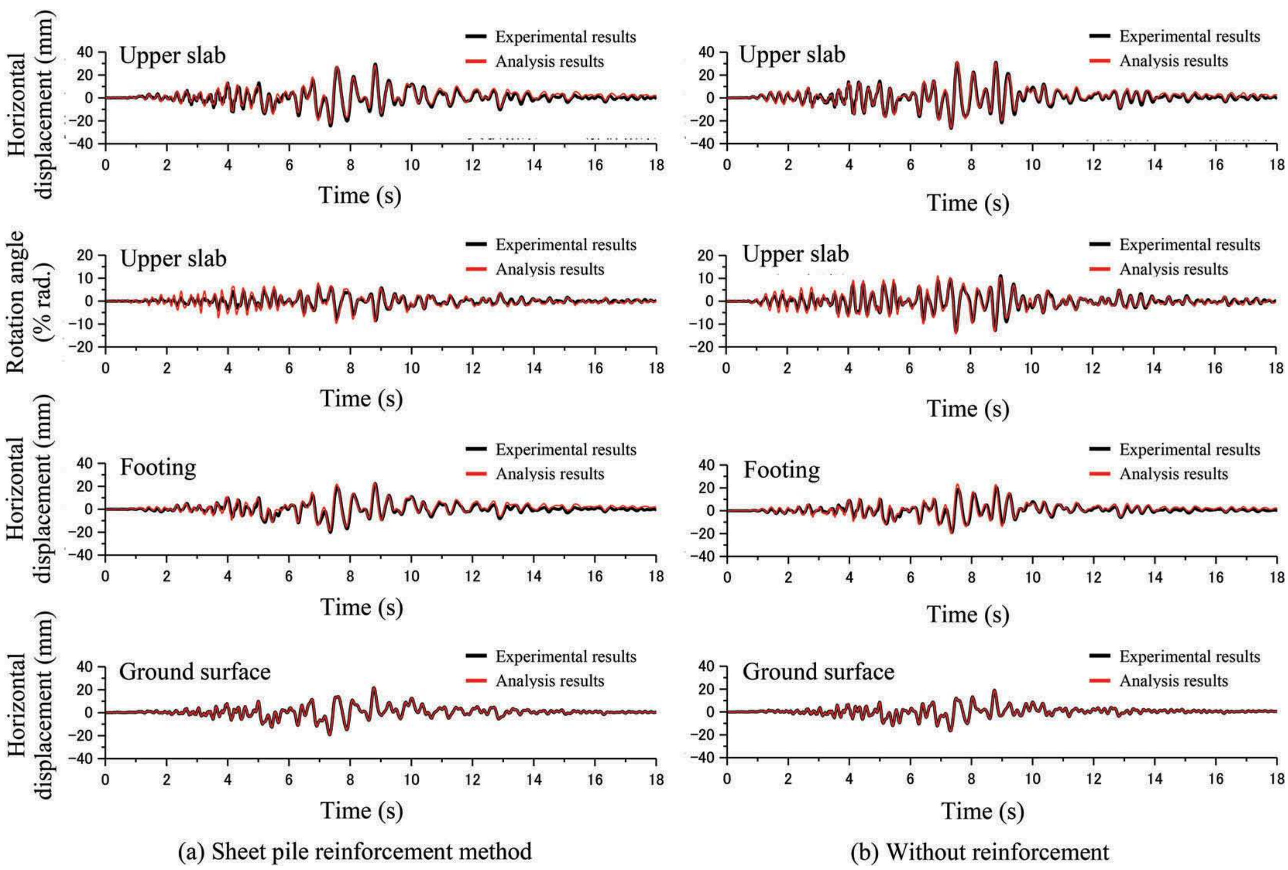


Figure 11. Comparison between experiment and analysis (time history response data).

response displacement, and Figure 12 shows the maximum bending moment distribution diagram. These results show that this analysis model can accurately reproduce the experimental results.

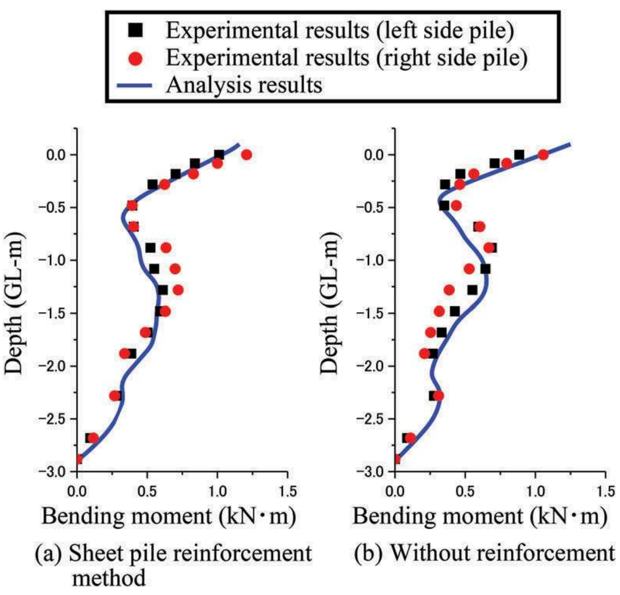


Figure 12. Comparison between experiment and analysis (Maximum bending moment distribution).

Consequently, we confirm that even a two-dimensional beam spring model can evaluate the behavior of the sheet pile reinforcement method for pile foundation structures in the liquefiable ground during an earthquake if several conditions can be evaluated accurately (the dynamic behavior of the liquefiable ground, the non-linear characteristics of the interacting spring, and the reduction in rigidity and strength of the soil spring due to an increase in excess pore water pressure).

4 TRIAL CALCULATION OF THE ACTUAL STRUCTURE (TODA ET AL. 2016)

We confirm the applicability of the two-dimensional beam spring model for the structural analysis of the sheet pile reinforcement method. In this chapter, we show how to consider the effect of liquefaction in the design of this reinforcement method. Additionally, we carried out the trial calculation.

Chapter 2, and 3 show an experimental and numerical analysis of the case of general structures. On the other hand, the previous study confirmed that when there was no superstructure, the response of the structure with the sheet pile reinforcement method may increase because the foundation structure was influenced by ground displacement (Matsuura at el. 2015). Therefore, we consider the ground model depending on the degree of liquefaction in this trial calculation by following the seismic design standard. Furthermore, in this trial design, we use a design method that combines static nonlinear analysis (pushover analysis) and nonlinear response spectrum method (Ministry of Land, Infrastructure, Transport and Tourism. 2012. Seismic Design). Firstly, the equivalent natural period and yield seismic intensity of the overall system of the structure is calculated from the relationship between the load and the displacement obtained by the static nonlinear analysis. Secondly, the response plasticity rate μ is obtained from the required yield seismic intensity spectrum (the relationship with the response plasticity rate μ when the horizontal axis is the equivalent natural period and the vertical axis is the yield seismic intensity). Finally, the nonlinear response is calculated by multiplying the response plasticity rate μ by the yield displacement.

To verifying the effect of the sheet pile reinforcement method on the liquefiable ground, we carried out the trial design for two cases: one was the case of the sheet pile reinforcement method and the other was the case of no countermeasures. Figure 13 shows a general view of the sheet pile reinforcement method and ground conditions. The liquefiable layer is the section of (2) sandy soil (Figure 13).

Figure 14 shows the load-displacement relationship obtained from the trial design results. We confirm that although the maximum response seismic intensity during liquefaction increases, the support yield of the existing pile and the shear failure of the pile head are suppressed because the deformation is suppressed by the sheet pile reinforcement method.

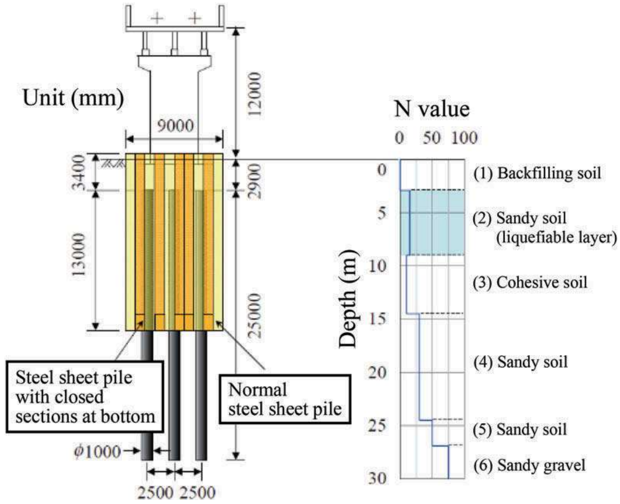


Figure 13. General diagram of sheet pile reinforcement method.

5 CONCLUSIONS

In this paper, we conduct model vibration experiments and numerical analysis so as to develop a reinforcement method with excellent economic efficiency and workability in the liquefiable ground. What we have learned from this research is below.

(1) In the case of structural conditions mainly based on inertial force, by carrying out the sheet pile reinforcement method, the displacement is suppressed and the cross-sectional force of the pile head is also reduced by the vertical resistance of the sheet piles.

(2) As a result of the reproduction analysis of the model vibration experiment by using a two-dimensional beam spring model, we can accurately reproduce the experimental results by

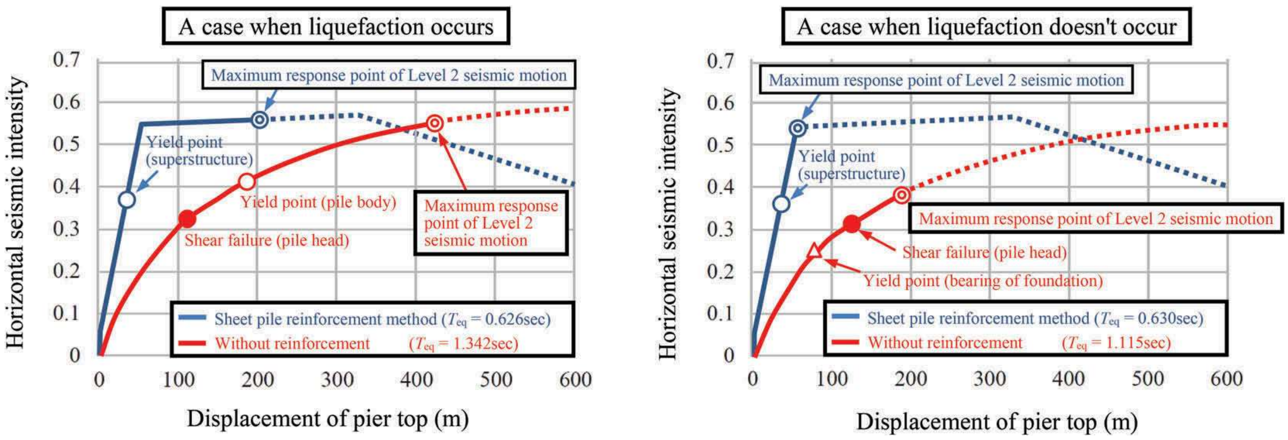


Figure 14. Relationship between load and displacement.

considering the dynamic behavior of the ground and the ground reaction force coefficient during liquefaction. Therefore, we consider that the design calculation can be performed using a general structural analysis model.

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