Report

Activities for the Reinforcement of Existing Foundations

Tomoyuki Suzuki

Group Leader of Steel Pipe Sheet Pile Foundation Team,
Technical Committee of Road and Railway,
Japanese Technical Association for Steel Pipe Piles and Sheet Piles

Much infrastructure, including roads, bridges and rivers, had been constructed during a period of rapid economic growth in Japan. It is thought that the age-related problems of these structures will become more tangible and accelerated, and measures to mitigate them are imperative. According to the Ministry of Land, Infrastructure, Transport and Tourism (MLIT), the percentage of road bridges over 50 years after construction was about 18 % in 2013 and is expected to be about 65 % in 2033. Under these circumstances, MLIT began to issue a “basic infrastructure life elongation plan” and to carry out intensive examinations and inspections. Accordingly, they have started taking measures such as renovation and reinforcement.

In response to this trend, the Japanese Technical Association for Steel Pipe Piles and Sheet Piles (JASPP) has conducted various studies for the reinforcement of existing foundations. As one of the main activities, utilization of steel pipe sheet pile foundation will be introduced in the next sections.

1. Characteristics of Steel Pipe Sheet Pile Foundation

The structural characteristics of steel pipe sheet pile foundation (Fig. 1) is that steel pipe sheet piles are installed in an enclosed form of circle, oval or rectangle, and the rigidity of the structure is increased by filling materials such as concrete mortar in the P-P shaped interlock. Features from the behavioural characteristics of wall structures such as those made of steel pipe sheet piles are that they depend mainly on the horizontal resistance of the ground, while the steel pipe sheet pile foundation depends on vertical resistance from the pile toe resistance and skin friction as well as horizontal resistance. From this viewpoint, the behaviour of steel pipe sheet pile foundation is closely related to the ground condition, and a more careful ground evaluation and more reliable construction are both required to secure highly reliable foundation structures. Therefore, several evaluations of the foundation performance including on-site loading test have been carried out, and standardized application methods have been shown only for structures and construction methods of which the execution management methods are specified in the Japanese Bridge Standard and all that. For the steel pipe sheet pile foundations, the pile driving method or foot protection method with inner excavation is currently regarded as the standard construction method, whereas the Press-in Method and the Press-in Method assisted with water jetting have not been generally used. For these two methods, it is prescribed that the pros and cons of their use and the design application be evaluated by carrying out construction tests and loading tests at each construction site. From the advantage that the cofferdam to build a bridge pier can be co-used, the steel pipe sheet pile foundation has shown itself to be highly economical as a foundation construction method in water areas,

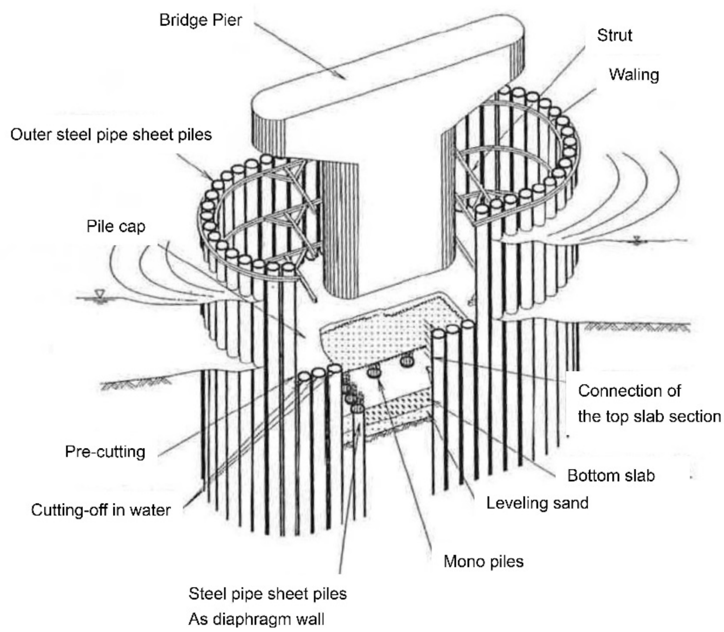


Fig. 1 Schematic view of steel pipe sheet pile foundation that is simultaneously used as temporary cofferdam

and its application has increased. To further increase its use, it is indispensable issue to develop a construction method that is highly applicable and reliable, so that the method can cope with many different ground and construction conditions.

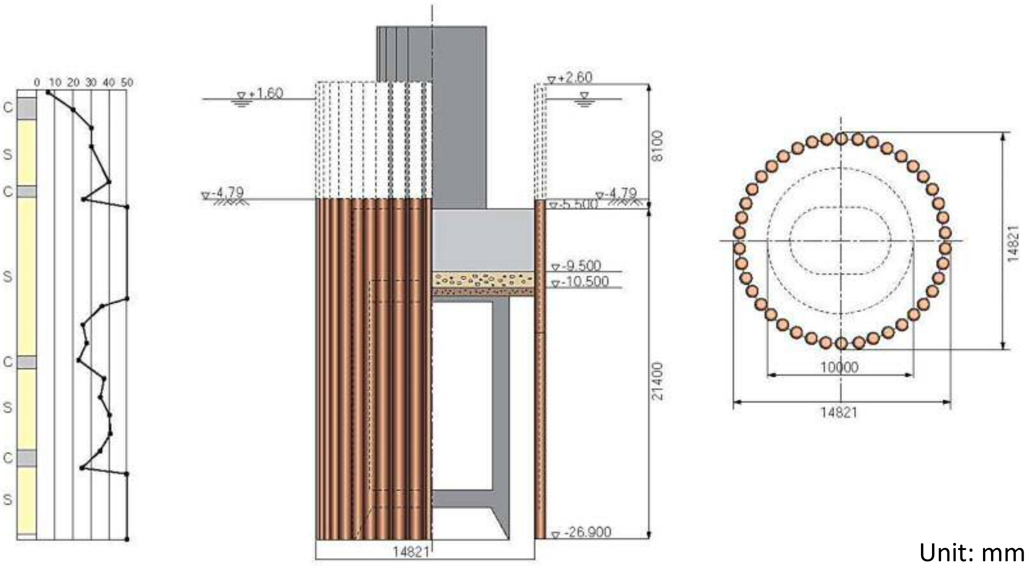
2. Activities for Reinforcement of Bridge Pier Foundation

Reinforcement methods of existing foundations may be divided into those increasing bearing capacity of foundation, e.g., by ground improvement, and those increasing bearing capacity structurally. Typical examples of the latter case maybe a method to add foundation piles by enlarging footing, and steel pipe sheet pile foundation extension method 1), 2). In the steel pipe sheet pile foundation extension method, steel pipe sheet piles are installed in such a way as to enclose an existing foundation, and a combined footing structure is formed by connecting the piles with the existing foundation using pile caps and so on. Table 1 shows main past records by the steel pipe sheet pile foundation extension method, while Fig. 2 depicts a reinforcement case. The reinforcement cases by the steel pipe sheet pile foundation extension method have increased since the restoration works of the Great Hanshin Earthquake Disaster. As described earlier, the steel pipe sheet pile foundation has an advantage that it can be used as a temporary cofferdam in reinforcement woks in water. In addition, there are key advantages of the Press-in Method, such as construction conditions of limited overhead clearance under bridge girders, and piling with limited harmful effect on existing foundations.

Table 1 Main reinforcement records by steel pipe sheet pile foundation extension method

Location In Japan	Existing foundation	Reason for reinforcement	Steel pipe sheet piles OD(mm)/Length(mm)	OD of coffer dam	Construction method
Miyazaki	Caisson foundation	Wash out	612.8/25500	Oval 11835 x 7593	Inner excavation + pre-boring
Wakayama	Caisson foundation	Upper work extension	600/10000	Oval 16254 x 6834	Inner excavation (cement milk)
Hyogo	Caisson foundation	Aseismic reinforcement	600/15500	Circular 7634 x 7634	
Hyogo	Caisson foundation	Aseismic reinforcement	600/13500	Circular 11635 x 7593	
Hyogo	Caisson foundation	Aseismic reinforcement	600/44600	Circular 8711 x 8711	JV (Vibro with WJ*)
Hyogo	Direct foundation	Wash out	600/8500	Oval 22078 x 11600	Inner excavation (cement milk)
Hyogo	Caisson foundation	Bridge widening	600/21500	Circular 14821 x 14821	Press-in Method (with WJ*)
Hyogo	Caisson foundation	Wash out	600/14000	Rectangular 14460 x 7200	Inner excavation
Osaka	Caisson foundation	Wash out	600/28500	Oval 15216 x 6834	Press-in Method (with WJ*)
Nara	Caisson foundation	Upper work extension	600/20500	Circular 10158 x 10158	--
Tokyo	Pile foundation	Aging	1000/36500	Oval 20079 x 42539	Press-in Method

*WJ: Water jetting



Unit: mm

Existing foundation: Caisson foundation Circular 10000 x 10000 x L21500
Reason of reinforcement: Reinforcement of the foundation for the increase in the vertical load after widening the bridge
Specification of the steel pipe sheet piles: 800mm dia. x t12 x L21500 Circular 14821x14821
Installation method: Press-in associated with water jetting

Fig. 2 Reinforcement example by the steel pipe sheet pile extension method

On the other hand, from a structural design viewpoint, a clearer understanding of the behavior has been regarded important in Japanese bridge foundations. Combined foundations, in which foundations with different resistant characteristics are combined, have not been generally used. For this reason, there are no unified design methods for the steel pipe sheet pile foundation extension method. In the actual design, evaluation has been carried out in each case. It seemed often the case that the design for the actions arising during earthquake was performed in such a way that only steel pipe sheet pile foundation would carry the seismic load, because not enough was understood regarding the resistance exhibiting ratio between the existing and extended parts, and on the stability of the structure as a combined foundation. Consequently, in consideration of more economical foundation reinforcement works, establishment of a rational design method became an issue, in which the load exhibiting ratio between the existing and extended portions is clarified. As a result, JASPP organized a study group to build a design method of the steel pipe sheet pile foundation extension method, and to develop more rational structures. The study group conducted centrifuge model experiments and a 3-D FE-analysis. In addition, based on the results of the study, applicability of the 2-D analysis was examined. All the study summary will be described in the following sections.

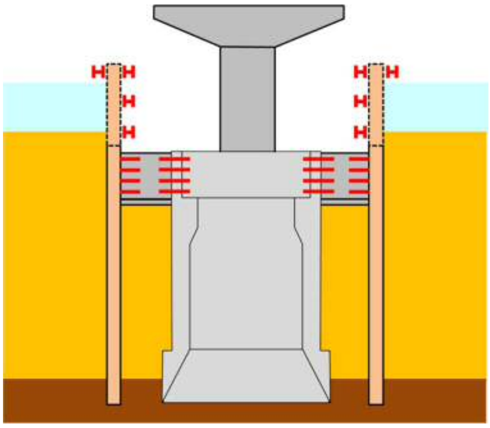
2.1 Centrifuge Model Test

Centrifuge model tests were carried out for 3 models, paying attention to the bonding structure of the steel pipe sheet pile foundation for existing caisson foundations: 1) rigidly fixed structure with pile caps; 2) semi-rigidly fixed structure with pile caps; and 3) unconnected structure without pile caps. Schematic diagrams of rigidly fixed and semi-rigidly fixed structures are observed in Fig. 3a and 3b, respectively. The following behavioral characteristics became clear:

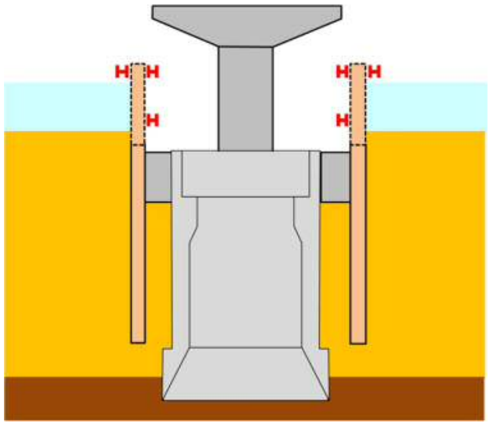
1) Rigidly fixed structure
From the beginning of loading, large reinforcement effect, horizontal yield strength of combined foundation divided by that of existing caisson foundation only, is shown. In the end, horizontal yield strength more than about 2.7 times the original value was obtained, compared with the situation before reinforcement by extension.

2) Semi-rigidly fixed structure

Horizontal resistances at the beginning and the end of loading increased by 60 % and more than 20 %, respectively.



a) Rigidly fixed structure



b) Semi-rigidly fixed structure

Fig. 3 Schematic view of pile cap connection method

3) Without pile caps

Effect by extension reinforcement was not noticeable.

From the result of the centrifuge model experiments, it may be concluded that the rigid fixing of extended structure with the existing foundation is the most effective connection method, and that the semi-rigidly fixed structure can be rational due to its simple connection structure, depending on the level of reinforcement effect required.

2.2 Three-Dimensional FE-analysis

To verify the reinforcement effect on real structures, a 3-D FE-analysis was conducted. The following points were clarified:

1) From the simulation analysis of the centrifuge model experiment, analytical conditions suitable for the steel pipe sheet pile foundation extension method were identified, and it was confirmed that the reinforcement effect could be quantitatively evaluated in the 3-D FE-analysis.

2) Though the increment ratio in horizontal yield strength may decrease for both rigidly fixed and semi-rigidly fixed structures as displacement increases, an increase in the yield strength of 1.5 to 2.0 times the original value was obtained. In the cases where pile caps were not used, the increase in horizontal yield strength was about 1.1 times the original value, not as good a reinforcement effect as in the centrifuge model test.

2.3 Two-Dimensional Analysis

To build a more simplified design method in lieu of a 3-D FE-analysis, 2-dimensional simulation analysis was carried out using real structural models, and its applicability was examined. The following points were clarified:

1) Load-deformation curves are compared between the 3-D FE-analysis and the 2-D analysis in Fig. 4. It may be seen in the figure that the load-deformation curves are generally in good agreement with each other. They are in good agreement, especially in the quasi-elastic range, where the horizontal seismic intensity is small. After the yield point, deformation in the 2-D analysis is somewhat larger.

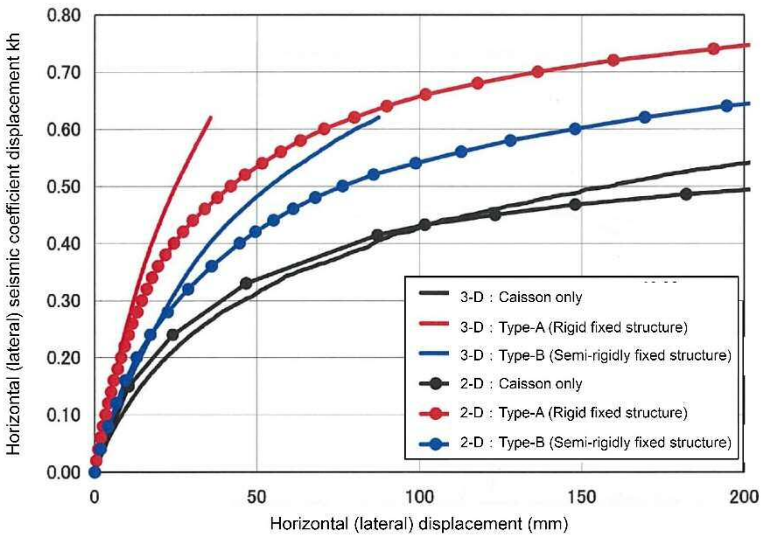
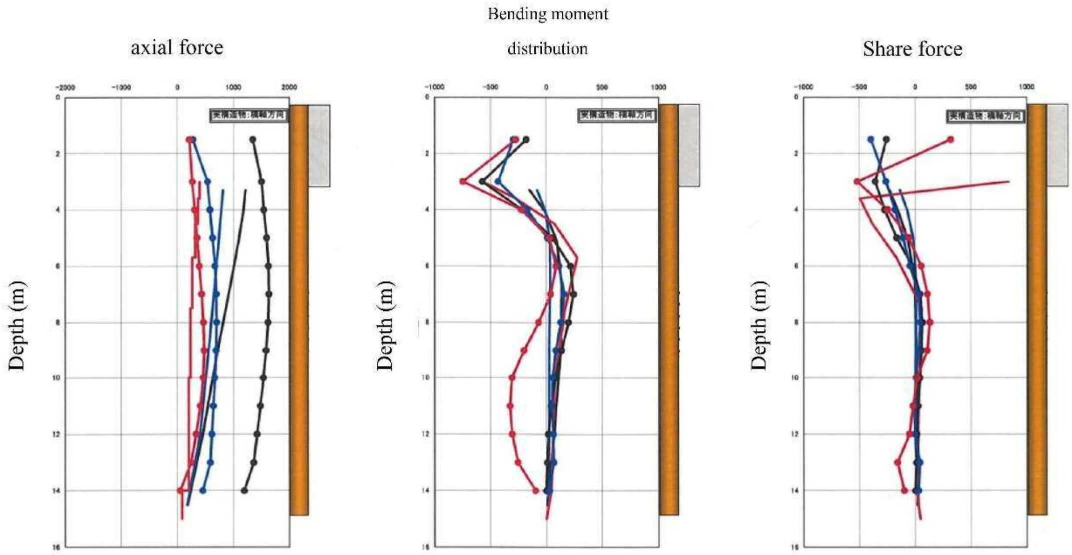


Fig. 4 Load-deformation curves: comparison of 2-D and 3-D analyses

2) As shown in Fig. 5, distributions of section force of the steel pipe sheet piles are generally consistent with each other, though there are some discrepancies between the two. There is a tendency that the absolute value of the section force is larger in the 2-D analysis result.



A） axial force distribution B） Bending moment distribution C） Shear force distribution

Fig. 5 Distribution of section forces exerted on steel pipe sheet pile

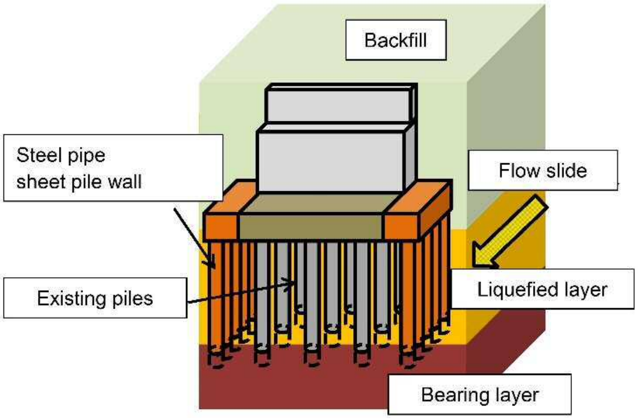
From the results obtained above, it may be concluded that the 2-D analysis can simulate relatively well the behavior of the foundation reinforced by the steel pipe sheet pile foundation extension method, that it gives more conservative results, and that it is applicable as a practical design method. Research results to date on aseismic reinforcement of existing foundations by the steel pipe sheet pile foundations have been discussed. From the findings obtained through this study, design method (draft) on reinforcement has been compiled as “Design manual for the steel pipe sheet pile foundation extension method (draft)”. For details, reference 2 may be referred to.

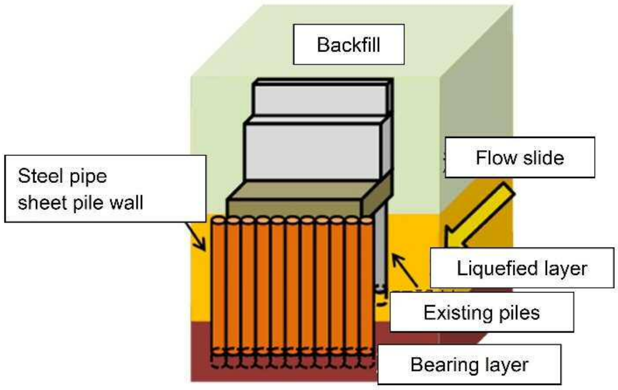
3. Activities for Reinforcement of Bridge Abutment Foundation

As a collaborative research with Research and development agency, Public Works Research Institute (PWRI), in a 4-year plan since 2015, JASPP has been developing reinforced structures of bridge abutment foundation on ground susceptible to liquefaction. The activities of this research have been carried out in a public-private partnership, as a “resilient reinforcement of disaster prevention/mitigation performance”, one of the Cross-ministerial Strategic Innovation Promotion Program (SIP)3) (termed SIP collaborative research, hereinafter). With the damage experienced at the time of the Great East Japan Earthquake as lessons learned, it is aimed to build a resilient society and reinforce disaster prevention/mitigation performance against the Nankai Megathrust Earthquake and any future earthquake that directly hits the Tokyo area. Fig. 6 shows a case study where a bridge abutment was damaged by the lateral movement due to liquefaction of the ground.

Fig. 6 Example of structure damaged by lateral movement due to liquefaction of ground

In this study, as a premise of taking reinforcement measurements while using road bridges, considered are the reinforcement methods that can produce a specified effect under the conditions such as no hindrance of common use of existing bridges, and limitation of construction area depending on road and structure conditions. An image of the reinforcement method is illustrated in Fig. 7.





A. steel pipe sheet pile wall, laterally integral type B. steel pipe sheet pile wall, front isolated type

Fig.7 Image of reinforcement method

As concrete activities, centrifuge model tests and shaking table experiments have been performed to date. Here, an overview of the shaking table tests and their results are explained 4). Schematic overview of the shaking table test is shown in Fig. 8, while two of the test cases performed are listed in Table 2. No reinforcement measure was taken in Case 1, whereas reinforcement by the laterally integrated type steel pipe sheet pile wall was made in Case 5. In the latter case, it is intended to suppress the deformation of the abutment by the steel pipe sheet pile wall during earthquake, and to secure the passability of the bridge after strong shake owe much to its vertical bearing capacity. Note that the shaking table tests were carried out using the 3-dimensional large-scale shaking table and a large scale rigid chamber with dimensions of 6 m wide, 3 m deep and 2 m high, both owned by PWRI.

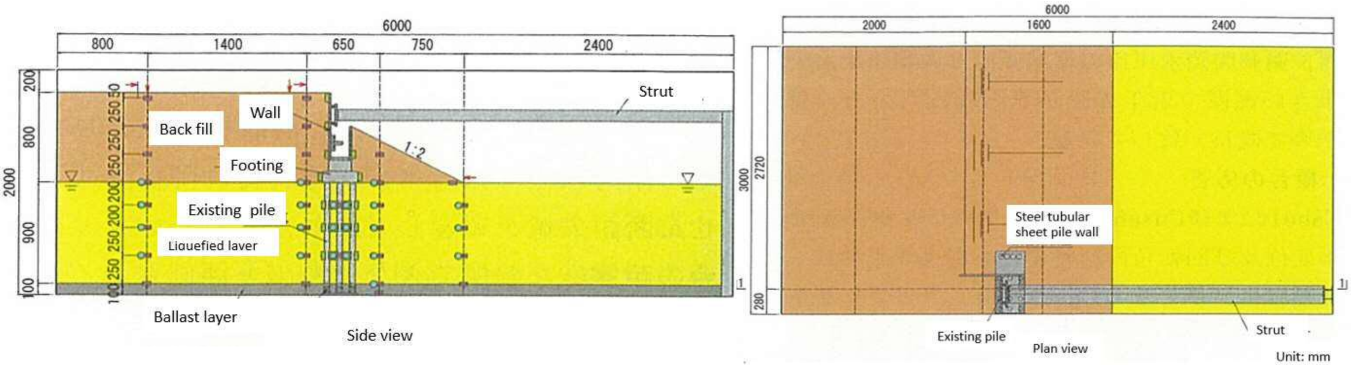


Fig. 8 Schematic view of shaking test

Table 2 Experimental cases considered

Case	Foundation dimensions	Reinforcement method
1	Prefabricated RC pile Diameter 450 mm, 8 x 3	No reinforcement
5	Prefabricated RC pile Diameter 450 mm, 8 x 3	Steel pipe sheet pile wall (laterally integrated type) 8 no. 600 mm dia., t = 9 mm piles (4 on each side)

Distributions of bending strain of existing piles at maximum response are shown in Figs. 9a and 9b, while that of reinforcement steel pipe sheet pile is shown in Fig. 9c. From the figures, the following observations may be made:

1) Distribution of bending strain of existing pile at maximum response

From Figs. 9a and 9b, it is shown that the magnitude and the distribution pattern of bending strain of the existing pile are both similar to those in Case 1, suggesting a similar range of earth pressure to that in Case 1 acted on the existing pile in Case 5. In addition, as in Case 1, at the top and in the middle section of the existing pile in Case 5, bending strain largely exceeded the yield strain.

2) Distribution of bending strain of reinforcement steel pipe pile at maximum response

Most bending strain of reinforcement steel pipe pile stayed within an elastic range.

From the results above, it may be said that even though bending strain of the existing pile largely exceeded the yield strain, aseismic property was still secured as a whole foundation after the existing pile was damaged, since reinforcement by the laterally integrated steel pipe sheet pile wall was a structure consisting of integrated steel pipe sheet pile wall and existing bridge abutment. Note that following these test results, a demonstration test with a large-scale model was carried out in February 2018, at a full-scale 3-dimensional vibration failure test facility (E-defense) owned by the research and develop agency, National Research Institute for Earth Sciences and Disaster Prevention (NIED). The test results are currently under compiling.

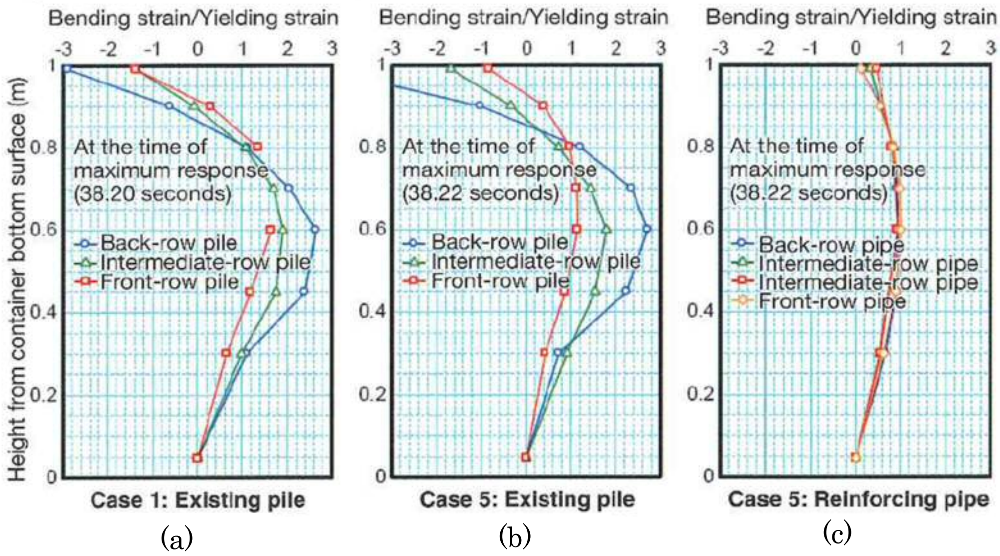


Fig. 9 Results of non-reinforcement (Case 1) and reinforcement by laterally integrated

4. Summary and Conclusions – Things Expected for the Press-in Method

When considering retrofitting of existing structures, the Press-in Method is expected to be one of the most effective construction methods, from the points of view of construction environmental conditions and effect on existing structures. In this case, the capacity that can install objects at a specified location is naturally required. In addition, another important factor may be the capacity to be able to accomplish this without disturbing the ground that is supporting the structures. More concretely, required for the construction method selected may be minimization of scattering the effects of the construction method on the ground, reduction in the vertical and horizontal resistance characteristics of constructed piles and steel pipe sheet pile, and improvement in reliability of load bearing performance. Specifications for highway bridges in Japan has been revised in a partial coefficient format based on reliability technique. Unfortunately, the observation data and analysis evaluation in views described above are not sufficient. As discussed in Section 1, the Press-in Method has not been regarded yet as a standard construction method for the Specification adopted for Road Bridges. Regarding further development of steel pipe sheet pile foundation in future and foundation piles installed by the Press-in Method, it is felt the urgent issue is to establish an execution management method that can guarantee standardization of construction and demonstration of specified performance and accumulate data on load bearing performance and its reliability.

Translated by Mr Masafumi Yamaguchi, IPA Secretariat

Reference

[1] Japan Road Association: Reference material on reinforcement of existing road bridge foundations, February 2000 (in Japanese).

[2] Study group of aseismic reinforcement, JASPP: Research report on steel pipe sheet pile foundation extension method, March 2007 (in Japanese).

[3] Cabinet Office of Japan: Website http://www8.cao.go.jp/cstp/gaiyo/sip/ Cross-ministerial Strategic Innovation Promotion Program (SIP) (in Japanese).

[4] Civil Engineering Journal: Shaking table experiment on aseismic reinforcement technology of existing bridge abutment foundation in liquefiable ground, Volume 59, No. 9, 2017 (in Japanese)