Seismic Retrofitting Sites for Existing Foundations

by

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ABSTRACT

Seismic retrofitting or liquefaction countermeasures of existing structures in urban cities are types of work executed under restrictive execution conditions: other structures stand nearby, and in the case of a bridge foundation, the space under the bridge girders is low. Model testing and analysis and execution testing were carried out to develop seismic retrofitting technology that is economical and has superior execution properties, even under restrictive execution conditions such as these. Based on the results, the authors have developed three micropile methods that are economical and have superior execution properties, even under harsh conditions.

KEYWORDS: Liquefaction countermeasure, Micropile, Overhead space restrictions, Pile group effect, Seismic retrofitting

1. INTRODUCTION

Since the Hyogo-ken Nanbu Earthquake (Kobe Earthquake) of 1995, the seismic design standards for highway bridges have been revised. It is, therefore, now necessary to perform seismic retrofitting of existing structures that have not been damaged. The seismic resistance of an overall bridge structural system is usually improved by retrofitting its piers, but their foundations must also be retrofitted. Retrofitting by steel plate lining has been established as a method for bridge piers, but when retrofitting their foundations, it is extremely difficult to obtain adequate execution space because of restrictions imposed by the space available under bridge girders and by nearby structures. Therefore, there are cases where it is difficult to apply the conventional additional pile or ground improvement methods.

The Public Works Research Institute conducted joint research with the Advanced Construction Technology Center and 12 private sector companies for three years beginning in 1999 in order to develop a seismic retrofitting method and a liquefaction countermeasure method that are not restricted by site conditions, even directly under an existing structure. As a result, three economical micropile methods with superior execution properties have been developed.

This report introduces the three micropile methods that have been established through this joint research and a description of the joint research.

2. OUTLINE OF THE MICROPILE METHODS

The joint research developed design methods and execution methods for three micropile methods as seismic retrofitting technologies for places with restrictive execution conditions such as the space directly under an existing structure. These micropile methods are the High Capacity Micropile Method, ST Micropile Method, and the Multi-Helix Micropile Method. Fig.1 shows

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retrofitting of an existing foundation by the micropile method, and the three methods are described below.

2.1 High Capacity Micropile Method

The High Capacity Micropile Method is executed by boring a hole in the ground with a boring machine, inserting deformed bars and high strength steel pipes into the ground, then pressure injecting grout into the bearing layer: a method that can be counted on to provide high skin friction capacity. This method can be executed in all kinds of ground including soft ground, gravel ground, and rock ground. Fig.2 shows the structure of a High Capacity Micropile. This method is a retrofitting method used in the United States.

2.2 ST Micropile Method

The ST Micropile Method is executed by pressure injecting and agitating cement milk to improve the ground, then boring another hole in the middle of the improved ground and inserting a steel pipe, and finally pressure injecting cement milk into the gap between the steel pipe and the wall of the hole. The method does not disrupt the natural ground very much during execution because its first step is ground improvement. Fig.3 shows the structure of an ST Micropile.

2.3 The Multi-Helix Micropile Method

The Multi-Helix Micropile Method is executed by attaching four blades with different external diameters to the tip of a small-diameter steel pipe in a tapered pattern at a fixed interval, then inserting the steel pipe directly into the ground by rotating it. This method can be used without discharging soil, because the steel pipe is inserted by rotating thrust. Fig.4 shows the structure of a Multi-Helix Micropile.

3. DESCRIPTION OF THE RESEARCH

The purpose of the joint research was to develop design and execution technologies to use micropiles for seismic retrofitting of existing foundations and prepare a manual of these technologies. It was, therefore, necessary to analyze the behavior of both individual micropiles and of pile foundations with piles of different diameters: specifically large existing piles and smaller micropiles. Therefore, in order to clarify the vertical bearing capacity and the horizontal resistance properties of individual micropiles and confirm their execution properties, vertical loading tests, horizontal loading tests, joint performance tests, and other tests and analysis of micropiles were performed for each execution method. And static model tests, dynamic model tests and centrifugal tests and analyses of models of pile foundations with piles of different diameters were performed. Finally, the results of these tests and analyses were summarized to prepare a micropile method manual.
Table 1 shows typical tests performed as part of this joint research. The results of the testing performed to develop the High Capacity Micropile Method, the results of static model horizontal loading tests and analyses of foundations with piles of different diameter, and the design method proposed based on these results are explained below.

3.1 Vertical Loading Test and Horizontal Loading Test of a Single Pile

3.1.1 Vertical loading test

3.1.1.1 Outline of the test

In order to clarify the vertical bearing capacity properties of High Capacity Micropiles, a vertical alternating loading test was performed. The specification of the High Capacity Micropile used for the test is shown in Fig.6, and the soil boring log of the test ground is shown in Fig.5.
Fig.6 shows the locations measured during the loading tests. Strain gauges were

installed on three sections inside the steel pipe and on six sections on the reinforcing bars. The loading was performed by alternating loading, push-in and pull-out to the non-linear range in the load – displacement relationship to clarify both displacement properties, and afterwards, by monotonic pull-out loading until the ultimate state.

3.1.1.2 Test results

Fig.7 shows the vertical loading - pile top displacement curve. Its yield pull-out strength was 900kN, its ultimate pull-out strength was 1,050kN, and it reached the ultimate state at displacement of approximately 10% of the pile diameter. It shows that because the gradients of the push-in and pull-out until near yield are almost identical, the axial spring constants in both directions are equal.

Fig.8 shows the axial force distribution. The axial force was calculated using the axial strain of each section, and assuming that the full section of the steel pipe, reinforcing bars, and grout that make up each part was effective. The figure confirms that the bearing capacity of a High Capacity Micropile is primarily a product of the skin friction capacity of the embedded part. Fig.9 shows the relationship of the skin friction capacity of the outside of the piles during pull-out with the average displacement of each part. The skin friction capacity of the outside surface of the pile is calculating by treating the steel pipe diameter and the hole diameter as the effective diameter in the non-embedded part and embedded parts respectively.

3.1.2 Horizontal loading test

3.1.2.1 Outline of the test

In order to clarify the horizontal resistance properties of a High Capacity Micropile, horizontal alternating loading testing was performed. Fig.10 shows the soil-boring log of the test ground.

Fig.11 shows the locations measured during the loading testing. On three steel pipes from their tops to a depth of 4.5m, strain gauges were installed on the inside of the steel pipes at a distance of 150mm from joints, and after pressure injection of the grout, the steel pipes were reinserted. Because strain gauges cannot be installed on steel pipe below that depth because of the execution procedure, in that part, strain gauges were installed on the reinforcing bars. Strain gauges were installed on the outside of the steel pipe at the ground surface after the completion of the execution. The loading method was alternating loading that was continued until the displacement reached 400mm on the final cycle.

3.1.2.2 Test results

Fig.12 shows the horizontal load – pile top displacement curve. On the final cycle, the maximum horizontal load was 160kN in the positive direction. From the values obtained by the strain gauges, the pile body (section (5)) almost reaches plastic moment when the horizontal load is 150kN, but no clear point of change or point where the residual displacement rises abruptly can be seen in the load – displacement curve. The above results have confirmed the superior ductility of a High-Capacity Micropile.

3.2 Static Model Horizontal Loading Test of Pile Foundations with Piles of Different Diameters

3.2.1 Outline of the test

Existing foundations are retrofitted by micropiles by installing many micropiles around the existing piles and connecting them to the footing. But the seismic retrofitting effects achieved by retrofitting a pile foundation with micropiles had not been adequately confirmed. So in order to clarify the behavior of a group of piles with different diameters, static loading testing of a model of a group of piles with different diameters was performed. And a simulation analysis was performed by the ductility design method in order to develop a design method that can be applied to rationally perform seismic retrofitting design of an existing foundation retrofitted by micropiles. The model actually used was an approximately 1/5 scale model of an actual pile foundation. The test was performed for the seven cases shown in Table 2: cases with varying intervals between the existing piles and the micropiles and varying angles of inclination of the micropiles. Fig.13 shows an outline of representative cases: case 4 and case 6. Fig.14 shows the loading test for case 3.

3.2.2 Test results

Fig.15 shows the load – displacement curves for each case. Fig.15 confirms that in case 4 and case 6, the retrofitting effects of the micropiles are greater than in case 3 that represents conditions before retrofitting. A comparison of the results for case 4 and case 5 with different spacing between the existing piles and micropiles shows that there is no conspicuous difference between the retrofitting effects according to the interval between piles. In case 6 where the micropiles were inclined, retrofitting effects of the micropiles were conspicuously greater than in case 4 and case 5. Case 7 was omitted from the analysis because the model was defective.

3.2.3 Comparison with the simulation analysis

The simulation analysis was performed based on the ductility design method, that is stipulated in the Design Specifications of Highway Bridges. For the analysis, a correction factor that accounts for the pile group effect was set so that the test results could be reproduced. Fig.16 compares the load – displacement curves obtained by the test results and by the analysis results for cases 3 to 6. As shown in Fig.16, the load – displacement relationships for all cases are reproduced with relatively high accuracy by appropriately setting the correction factors. Similarly to the test results, there are almost no differences in the analysis results for case 4 and case 5, and it is assumed that increasing the spacing between the existing piles and micropiles has little effect on the retrofitting effects.

Fig.17 and Fig.18 show the bending moment distribution and the shear force distribution of the existing piles in case 3 and the existing piles and the retrofitted piles in case 4 obtained by the testing and by the analysis, In both cases, the distribution of the bending moment and the location of its maximum value obtained by the analysis closely resemble those obtained by the testing. The shear force in the analysis results also closely resembles that from the testing results.

The testing confirmed that retrofitting a pile foundation with micropiles obtains retrofitting effects. It also confirmed that installing the micropiles at an angle increases the retrofitting effects.
The ductility design method confirmed that it is possible to perform design that appropriately reflects the retrofitting effects of micropiles.

3.3 Design method for the High-Capacity Micropile Method

Based on the results of the testing described in 3.1 and 3.2, a vertical bearing capacity estimation equation for High-Capacity Micropiles and a design method for a pile group consisting of piles of different diameters are proposed.

3.3.1 Vertical bearing capacity estimation equation for High-Capacity Micropiles

The vertical bearing capacity of a High-Capacity Micropile is calculated to guarantee a safety factor for the ultimate bearing capacity determined by the ground in compliance with the Design Specifications of Highway Bridges.

The results of the loading testing described in 3.1 have revealed that the bearing capacity of a High-Capacity Micropile is provided by the skin friction capacity of the embedded part, that the bearing capacity of the tip is predicted to be very low because its diameter is small, and the skin friction capacity of the non-embedded part is also low. Therefore, the ultimate bearing capacity of a High-Capacity Micropile is calculated by accounting only for the skin friction capacity of the embedded part, but not accounting for the bearing capacity of the tip and the skin friction capacity of the non-embedded part of a High-Capacity Micropile.

Because a High-Capacity Micropile consists of a non-embedded part at the top of the pile such as a ground anchor plus grout in the bearing layer, and an embedded part that provides friction resistance against the ground, and because the maximum skin friction force (measured value) obtained from the vertical testing exceeds the average maximum friction force (design value) obtained based on the ground anchor design and execution standards as shown in Table 3, the maximum skin friction force of a High-Capacity Micropile used was the average value of the ground anchor design and execution standard as shown in Table 4.

3.3.2 Effects of a pile group with piles of different diameters

Even in a case where an existing pile foundation is seismically retrofitted by micropiles, it is assumed that it is designed using the ductility design method stipulated by the Design Specifications of Highway Bridges. Ductility design models the resistance characteristics at right angles to the axis of a pile as an elasto-plastic model with the upper limit value of the horizontal subgrade reaction P_{HU} and with the coefficient of horizontal subgrade reaction k_{HE} as the initial gradient. In the case of a pile group of piles with an identical diameter, the effects of the pile group are considered by correcting the values k_{HE} and P_{HU}. The results of static model testing confirmed that even in cases where the pile foundation is made of piles with different diameters, the pile group effect is identical to that of a pile group of identical piles. And the simulation analysis of the static model testing precisely reproduced the test results by correcting the values k_{HE} and P_{HU}, even though the results differed from those of the ductility method. Consequently, it is possible to design retrofitting by micropiles accounting appropriately for the retrofitting effects by modeling as shown below.

(1) It is a rigid frame structure in which the footing is a rigid body and the tops of the existing pile and micropiles are rigidly connected to the footing.

(2) The resistance properties in the axis direction of the micropiles are modeled as an elasto-plastic model with an upper limit of the push-in bearing capacity and an upper limit of the pull-out bearing capacity, and by treating the spring constant in the axial direction of the micropile as the initial gradient.

(3) The resistance properties in the direction at right angles to the axes of the micropiles and the existing pile are modeled as an elasto-plastic model with an upper limit value of the horizontal subgrade reaction P_{HU} while treating the coefficient of horizontal subgrade reaction k_{HE} as the initial gradient. P_{hu} is corrected by the ratio of the pile interval and pile diameter in the direction at right angles to the loading. And in sandy ground it is corrected by the ratio shown in Table 5.

(4) The bending moment – curvature relationship of a micropile is modeled as an elasto-plastic model, accounting for the loss of bending rigidity of the pile body according to the axial force and bending moment acting on the pile body.

4. CONCLUSIONS

The joint research program established design methods and execution methods for three micropile methods.
At this time, these have not been applied to actual work very often. But it has been confirmed that they provide superior execution properties under restrictive execution conditions.
Design and execution manuals for the three methods are prepared and it is assumed that in the future, they will be applied to the seismic retrofitting of existing foundations under restrictive execution conditions.

5. REFERENCES

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Table 1 Major Experiments in this project

	High Capacity Micropile	ST Micropile	Multi-Helix Micropile
Common Experiments	Static Lateral Load Testing of Model Foundations with different kind of piles Dynamic Lateral Load Testing of Model Foundations with different kind of piles Loading Tests in a Centrifuge		
Special Experiments	Bending Tests Vertical Loading Tests Lateral Loading Tests Tests for Workability (Vertical and incline piles) Tests for the connection of Steel Piles Pull Tests for the connection of Pile Head	Vertical Loading Tests Lateral Loading Tests Tests for Workability Tests for the connection of Steel Piles Skin Friction Tests	Vertical Loading Tests Tests for Workability Tests for the connection of Steel Piles

Table 2 Cases of Static Horizontal Loading Tests

Case	Number of Piles	Spacing between Existing Piles Center and Micropiles Center (mm)	Inclination Angle of Micropiles (°)	Loading Method
1	Single Existing Pile	–	–	One Direction
2	Single Micropile	–	–	One Direction
3	4 Existing Piles	–	–	One Direction
4	4 Existing Piles and 6 Micropiles	200	0	Cyclic
5	4 Existing Piles and 6 Micropiles	400	0	One Direction
6	4 Existing Piles and 6 Micropiles	200	10	One Direction
7	4 Existing Piles and 6 Micropiles	200	20	One Direction

Table 3 Comparison of the Design Values with the Results of Vertical Loading Tests

Vertical loading test	Ground condition	Maximum friction (N/mm^2)	
		Measured value	Design value
Push-in loading	Hard clay layer c=0.87 N/mm^2	1.00	0.87
	Fine sand layer N-value =20	0.25	0.21
Pull-out loading※	Fine sand layer Average N-value =40	0.32	0.32

※ Test Results of (1)

Table 4 Maximum Skin Friction f_i

Type of ground			Friction Strength (N/mm^2) in "Design and Execution Specification for Ground Anchor"	Max. skin friction (N/mm^2)
Rock	Hard rock		1.5−2.5	2.00
	Soft rock		1.0−1.5	1.25
	Weathered rock		0.6−1.0	0.80
	Hard clay		0.6−1.2	0.90
Gravel	*N* value	10	0.10−0.20	0.15
		20	0.17−0.25	0.21
		30	0.25−0.35	0.30
		40	0.35−0.45	0.40
		50	0.45−0.70	0.57
Sand	*N* value	10	0.10−0.14	0.12
		20	0.18−0.22	0.20
		30	0.23−0.27	0.25
		40	0.29−0.35	0.32
		50	0.30−0.40	0.35
Cohesive soil			1.0 c (c is cohesion)	1.0 c (c is cohesion)

Table 5 Compensation Factor of p_{HU} in Sandy Ground

	Micropile		Exsiting Pile	
	Front Pile	**Others**	**Front Pile**	**Others**
Sand Layer	**1.00**	**0.50**	**1.00**	**0.50**

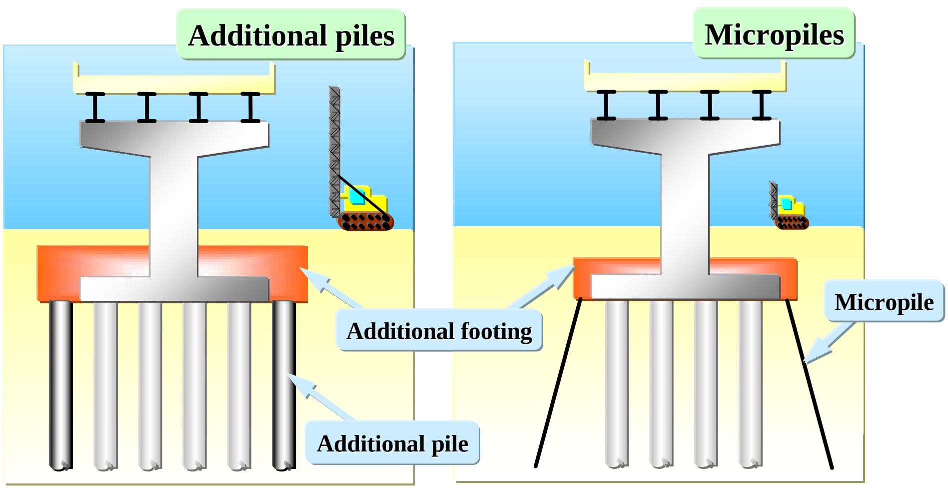


Fig.1 Image of Retrofitting by Micropiles

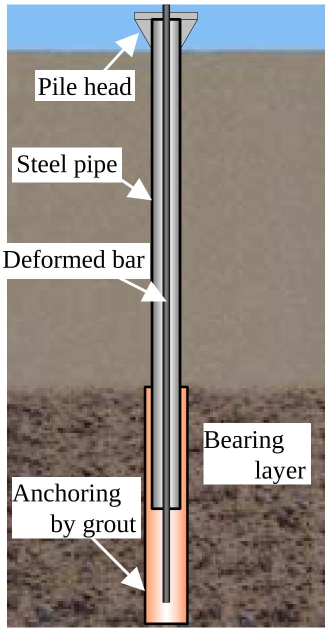


Fig.2
High Capacity Micropile

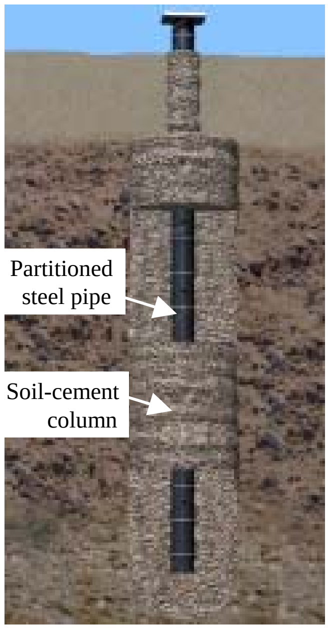


Fig.3
ST Micropile

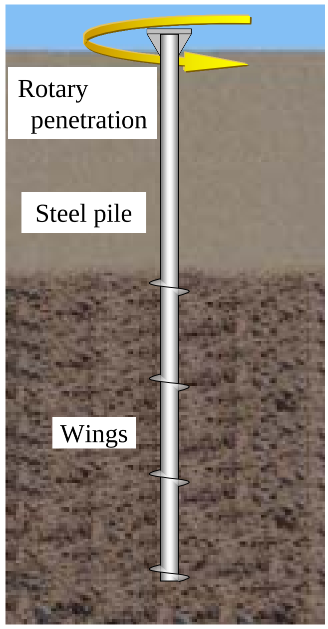


Fig.4
Multi-Helix Micropile

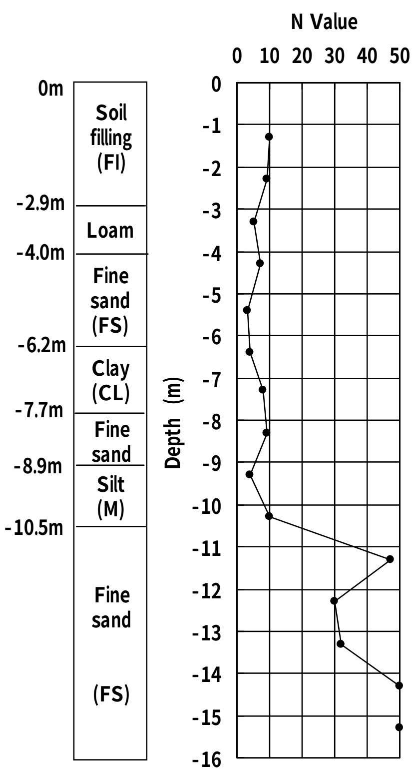


Fig.5 Soil Boring Log

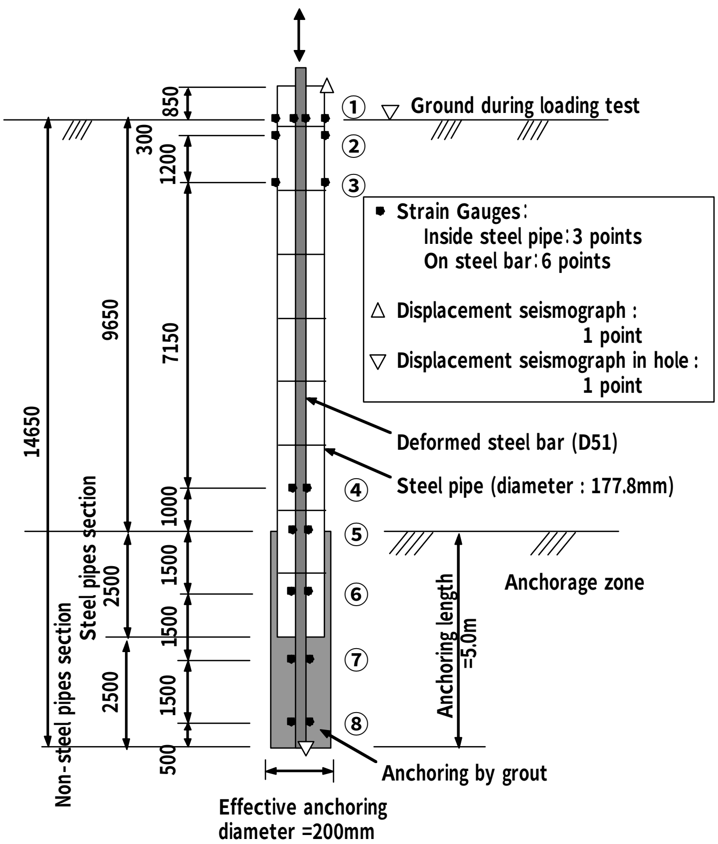


Fig.6 Locations of Measurement

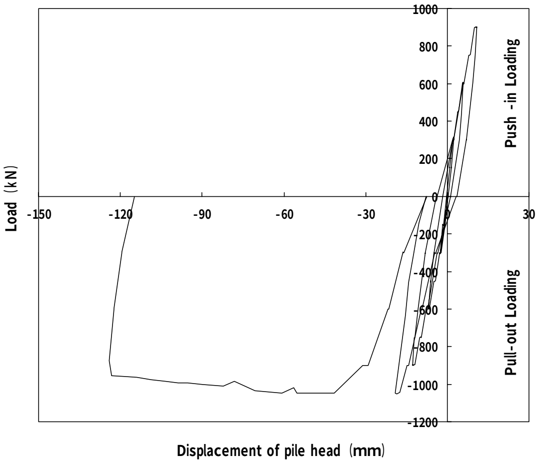


Fig.7 Hysterisis Curve of Load-Pile Head Displacement

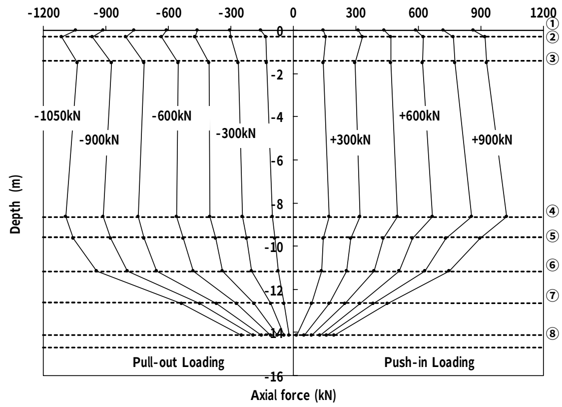


Fig.8 Axial Force Diagram

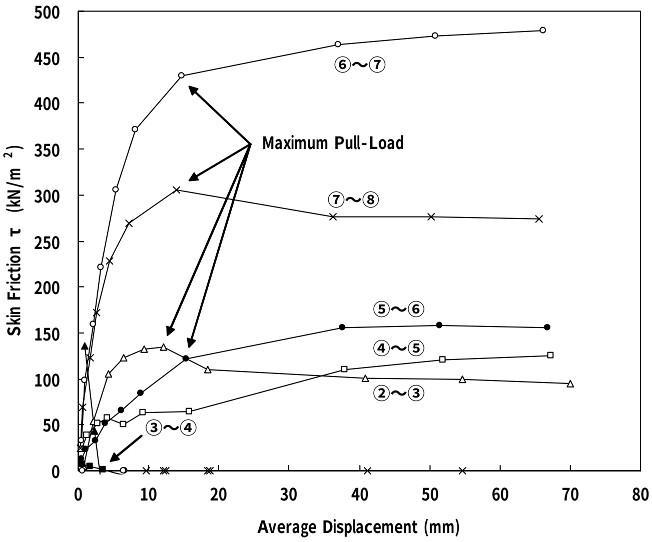


Fig.9 Skin Friction Capacity

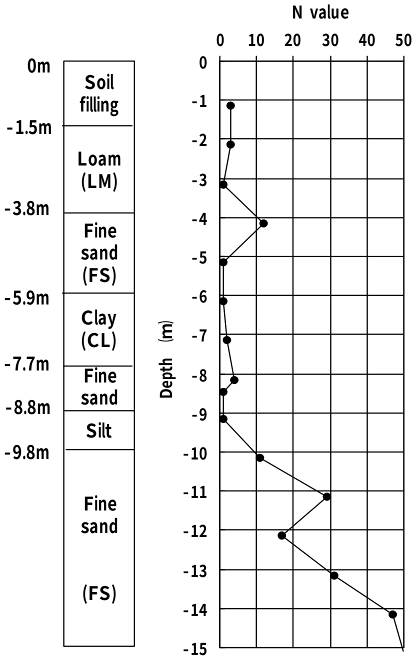


Fig.10 Soil Boring Log

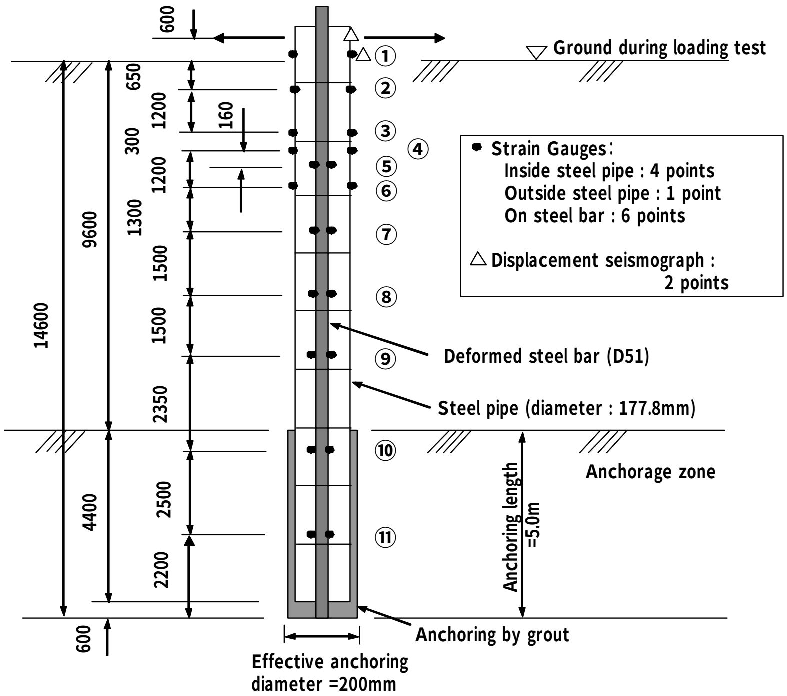


Fig.11 Locations of Measurement

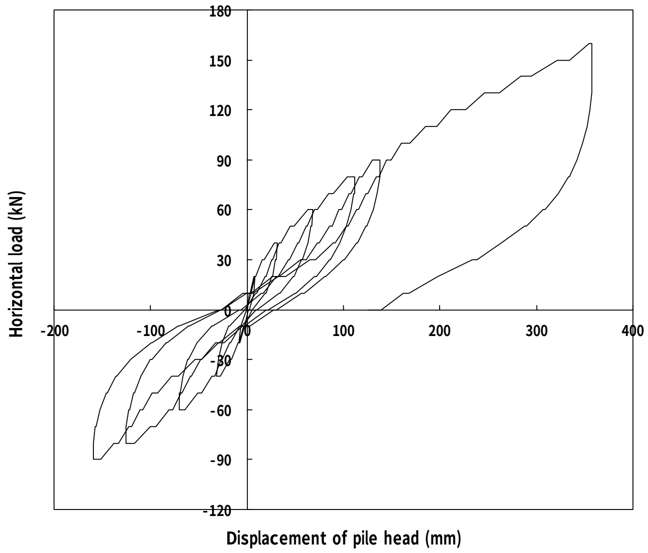


Fig.12 Hysterisis Curve of Load-Pile Head Displacement

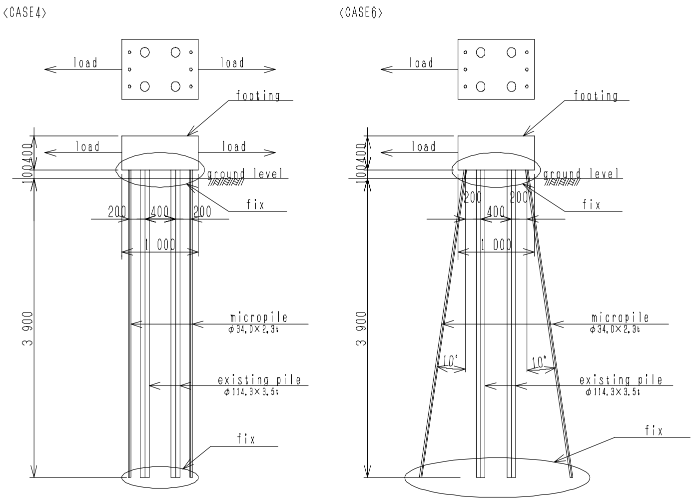


Fig.13 Outline of Case 4 and Case 6 Test Models

Fig.14 Loading Test for Case-3

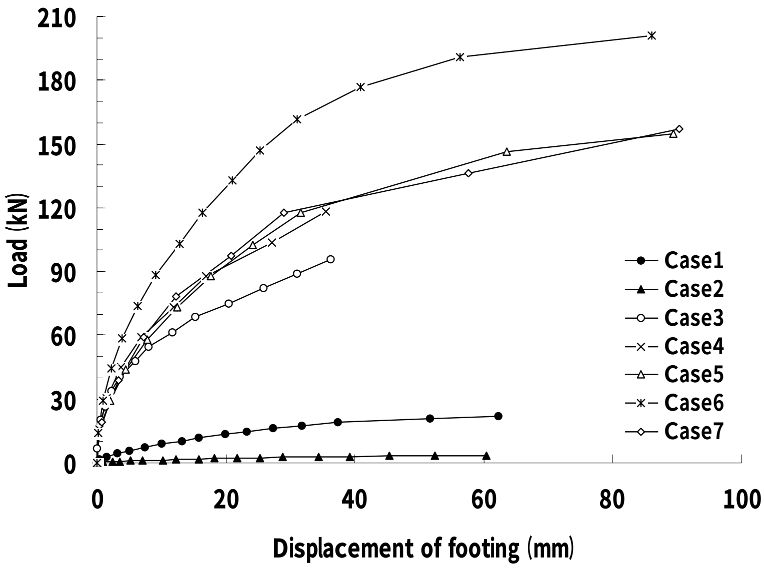


Fig.15 Load and Displacement Curves of Loading Test Results

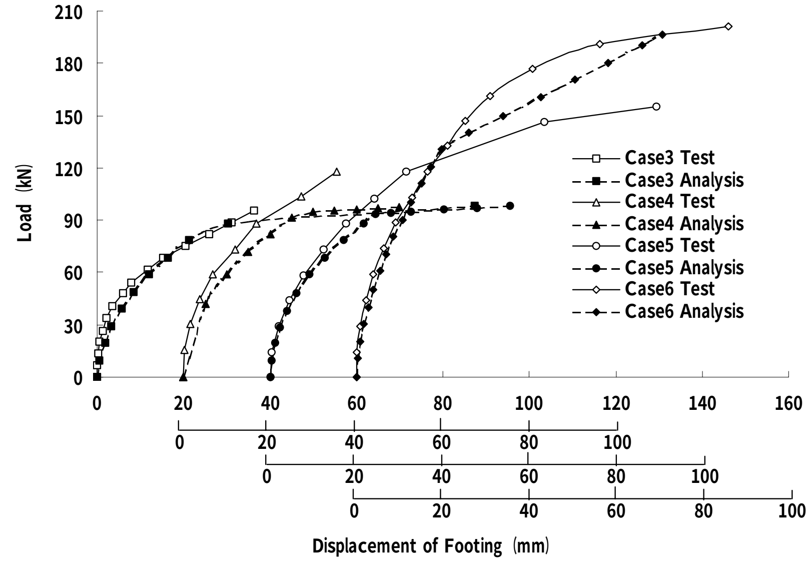
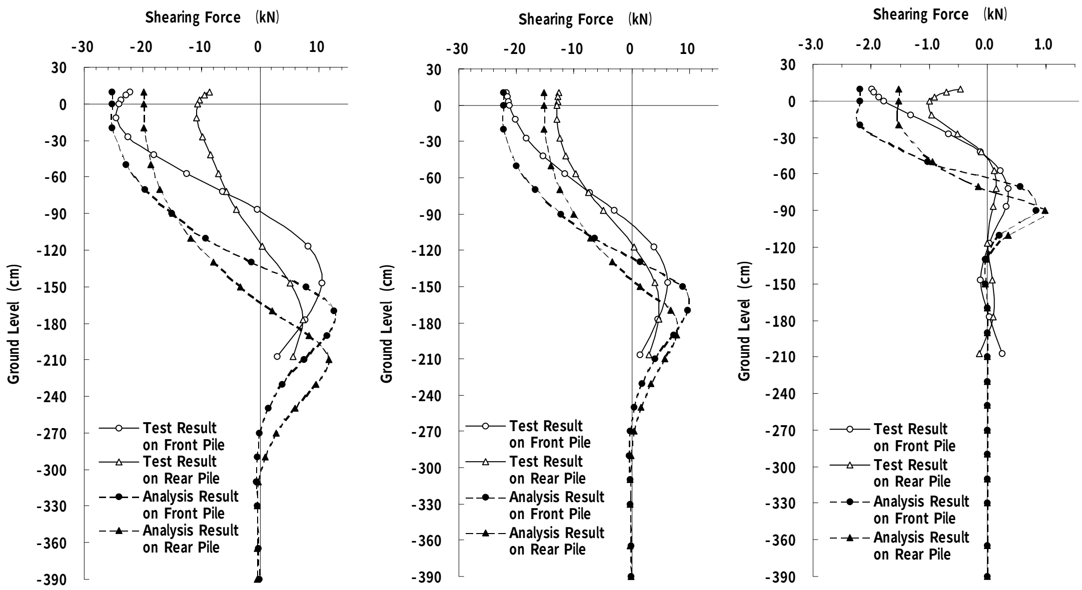


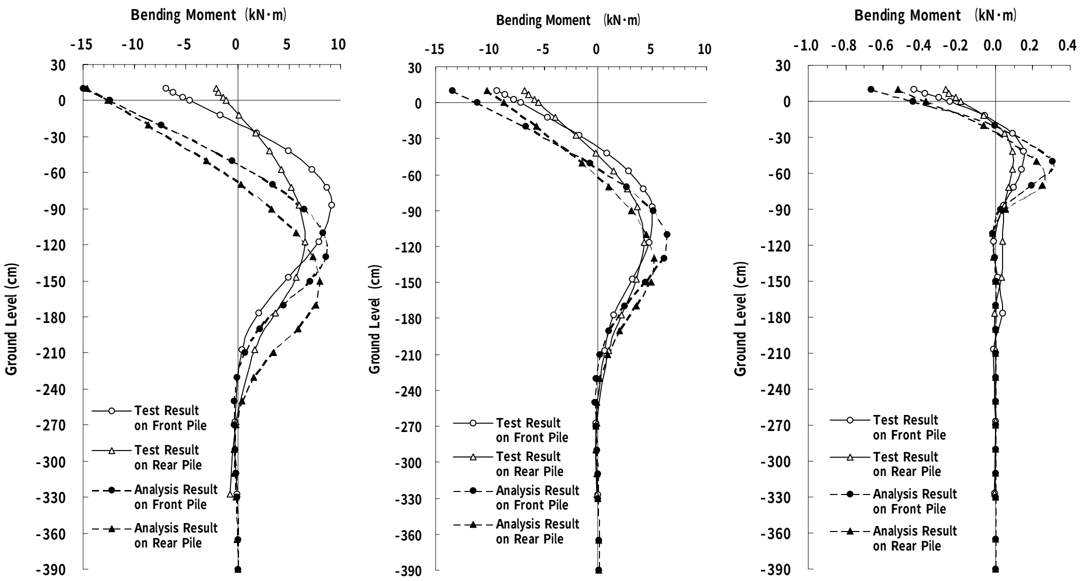
Fig.16 Comparison Loading Test Result with Analytical Results



Existing Pile Existing Pile Micropile

Case-3 Case-4

Fig.17 Bending Moment in Loading Tests and Analysis



Existing Pile | Existing Pile | Micropile

Case-3 | Case-4

Fig.18 Shearing Force in Loading Tests and Analysis