STATE-OF-THE-ART: APPLICATION OF MICROPILES IN JAPAN

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Micropiles in Japan : Present Status and Future Prospects

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1. Introduction

Developed in Italy in the 1950s, micropile technics were first used in Japan as protection for a lookout tower close to a shield tunnel construction in 1980. Since that time, they have been used primarily to stabilize slopes and as foundations for small scale structures.

After the Hyogoken- Nanbu Earthquake, many cases of pile foundations damaged by ground liquefaction etc. were reported. When restoring pile foundations damaged in this way, it is important to choose the reinforcement method, placing more piles or improving the surrounding ground for example, most appropriate for the level of damage in each case. Though it difficult to use large construction machinery at some sites, raising expectations that the more efficient micropile method would be effective at such sites. In fact, in recent years, micropiles have been used for seismic retrofit work at many sites in the United States.

This report introduces work performed using micropiles in Japan, explains design , construction , and quality control methods now in use,and reports on the future outlook for the method: issues to be resolved to permit its use for seismic retrofit work for example.

2. Experience of Micropile Constructions in Japan

Figure 1. shows a classification of applications which micropiles are used in Japan.

And Figure 2 shows the percentages of all micropile work in Japan in various work categories. It indicates that much micropile work is undertaken as an in- situ earth reinforcement measure such as landslide stabilization and cut slope reinforcement , with about 80% of all past work performed for this purpose.

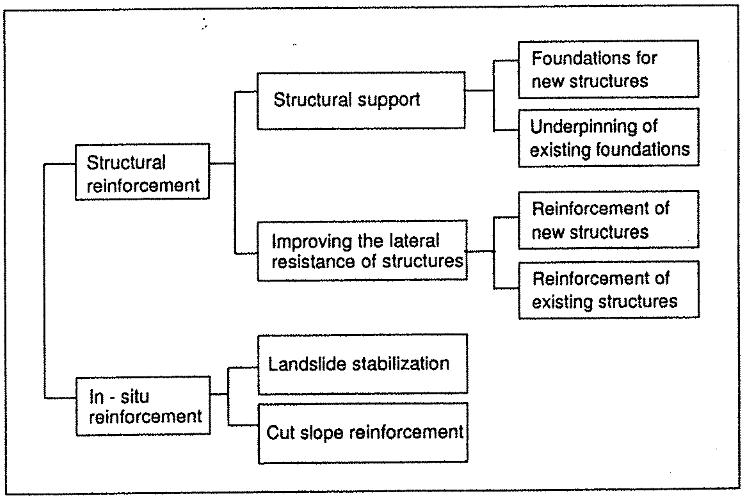
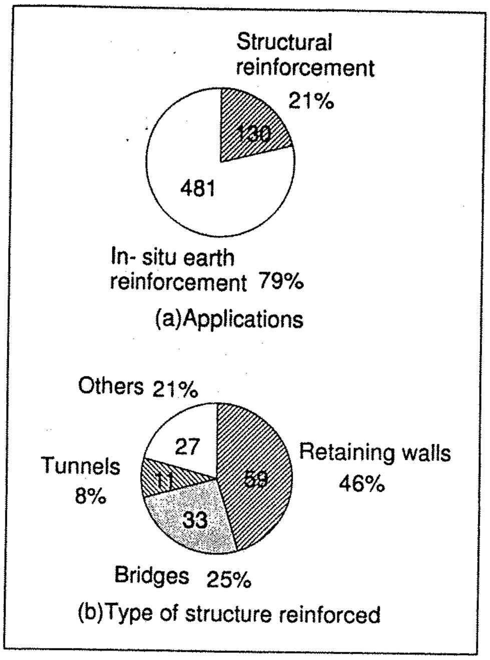


Figure 1. Classification of micropile applications in Japan



(a)Applications

(b)Type of structure reinforced

Figure 2. Distribution of Micropile Work in Japan By Work Category

Micropiles have seldom been used as the foundation for a new structure, and when they have, it has almost been for a small scale bridge abutment or retaining wall where ground conditions were poor. Micropiles have been used many times as underpinning of existing foundations. In these cases, micropiles were placed by small construction machinery because restrictions on space under the girder prevented the use of other methods. In a few cases, micropiles were used as a seismic retrofit method following the Hyogoken- Nanbu Earthquake. These cases differ from the seismic retrofit method using high capacity micropiles at bridge foundations as is done in the United States. In Hyogo Prefecture, micropiles were placed behind structures as an insitu earth reinforcement measure at damaged small scale bridge abutments and retaining walls, and the work was designed to bear laterall loads.

Figures 3 to 8 present outlines of typical constructions in Japan.

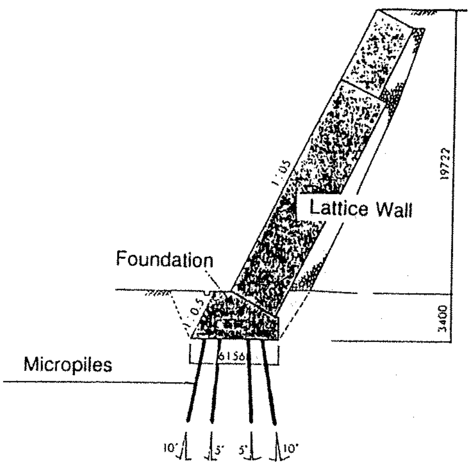


Figure 3.New retaining wall foundations

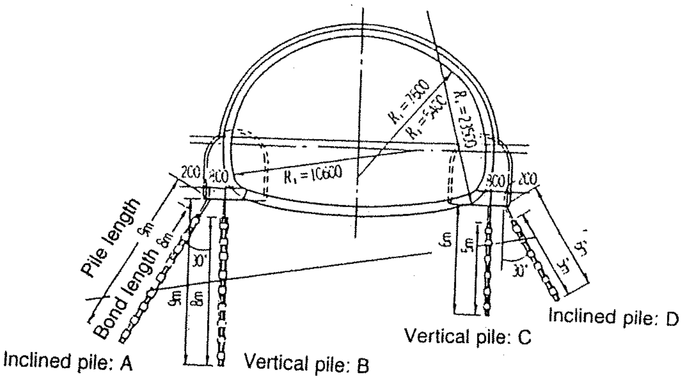


Figure 4.Tunnel foot reinforcement

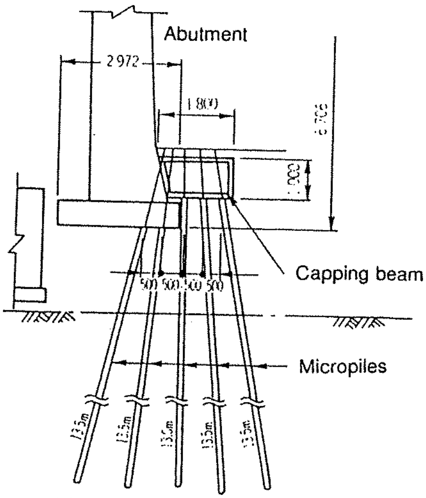


Figure 5.Underpinning of an existing abutment

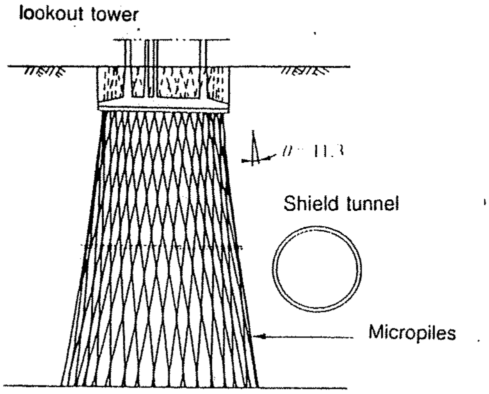


Figure 6.Protection of an existing structure

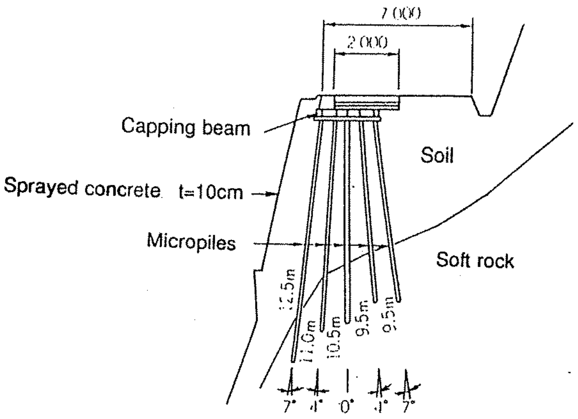


Figure 7.Landslide stabilization

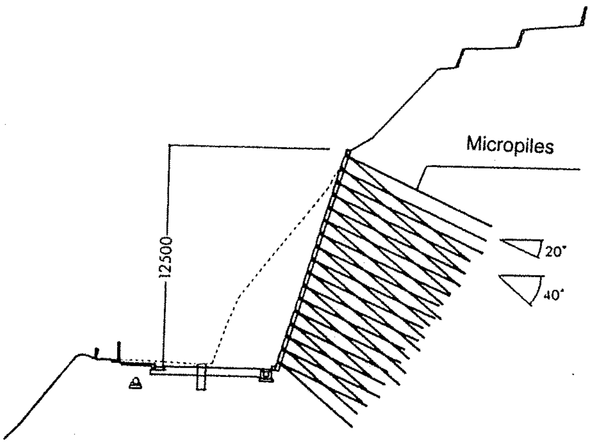


Figure 8.Cut slope reinforcement

Table 1 presents the example of specifications of micropiles by form for reinforcement based on past constructions. As it indicates, the diameter and length of piles used in Japan are not as great as those of piles used in the United States.

Table 1.Example of specifications of micropiles by form for reinforcement

Form of reinforcement	Pile diameter (mm)	Pile length (m)
Compression reinforcement	115 - 135	4.0 - 25.0
Tension reinforcement	60 - 115	4.0 - 15.0

3. Outline of Design Methods in Japan

The following are two concepts applied to micropile design as the cross section which resists load.

(a)The compressive force is resisted by the reinforcing steel and the grout, while the tension force is resisted by the reinforcing steel.

(b)The compressive force is resisted by a compound body consisting of piles and the surrounding ground reinforced by piles, and the tension force is resisted by the reinforcing steel.

The latter concept relies upon the group effect (or the network effect) of the micropiles. In Italy, Japan, etc., this concept is applied to design work for micropile work used as in-situ earth reinforcement. The following is the cross section calculation equation for this case. The mortar equivalent cross sectional area (A_p) of the micropiles is represented by the following equation.

$$A_p = n\cdot A_s + (A_c - A_s) = (n-1)A_s + A_c \quad (1)$$

Where:

n: Mortar/reinforcing steel elastic modulus ratio (n = 15)

A_p :Mortar equivalent cross section area of the micropile

A_c : Pile cross section area

A_s : Reinforcing steel cross section area

The soil equivalent cross sectional area (A_{soil}) of the compound body formed by the piles and surrounding ground is represented by the following equation.

$$A_{soil} = m \cdot A_p \cdot S + A \quad (2)$$

Where:

m: Pile/surrounding ground elastic modulus ratio

S: Number of piles included within the datum plane being studied

A: Net cross section area of the reinforced soil body formed by the pile and the surrounding ground.

In the United States, buckling is studied in the case of soft ground, but in Japan buckling is hardly ever studied. It is not studied because the tops of the micropiles are connected by a capping beam and their placement interval is very dense (1 pile every 0.5 to 1 m^2).

4. Construction Method and Quality Control Method

4.1 Material

(1) Reinforcing Steel

The reinforcing steel used includes deformed bars, steel pipe, steel bars for prestressed concrete, and steel strands for prestressed concrete. In Japan, deformed bars (refer to Table 2) are used in almost all cases, but the steel pipe presented in Table 3 is used as foot reinforcement in tunnels. And to increase the adhesion effect, steel flanges are attached to the deformed bars or steel pipes at fixed intervals.

Figure 9 presents the typical shapes of deformed bars and steel pipes when used as reinforcing steel. In the United States, steel pipes are often used to limit displacement or to resist large lateral load, but in Japan, deformed bars are almost always used for these purposes.

(2) Grout

Grout is either mortar or cement paste. Mortar is normally used, but when the action of weathering has created fine cracking of the natural ground, cement paste is used. The cement is usually ordinary Portland Cement (JIS R 5210), but on river reservations and other places where the ground water flows or in cases where fast hardening is necessary to maintain the work schedule, early strength or ultra- high early strength Portland Cement is used. The mortar or cement paste contains a water reducing agent, expansion agent, or other admixture, but when this is done, as a standard, its strength σ_{CR} is greater than 23.5 N/mm^2 and its flow value is 19 ± 3 seconds.

(3) Other Materials

The other materials used are capping beams, shape steel, steel spacers, and so on. Capping beams are reinforced concrete members used to link the tops of the individual micropiles. Shape steel is material used for the same purpose, but it is normally used on steep slopes and other places where it would be difficult to use a capping beam. Steel spacers are used to hold the reinforcing steel in the center of drilled holes to equalize the thickness of the grout covering, and generally, one is installed for every 2 m of reinforcing steel.

4.2 Construction Procedure

Figure 10 presents the normal micropile construction procedure.

(1) Drilling

It is important to consider the location, its topography, and its geology, then select the drilling method best suited to these conditions from among the rotary, percussion, drilling with used water, or air flush drilling methods. The casing usually has an external diameter between 65 mm and 200 mm and is between

Table 2.Mechanical properties of threaded deformed bars(taken from JIS G 3112)

Grade		Code	Tensile strength (N/mm ^{2})	Yield point (N/mm ^{2})
Hot rolled deformed bars	Grade1	SD24	382 - 519	more than 235
	Grade2	SD30	480 - 617	more than 294
	Grade3	SD35	more than 490	more than 343
	Grade4	SD40	more than 559	more than 392
	Grade5	SD50	more than 617	more than 490

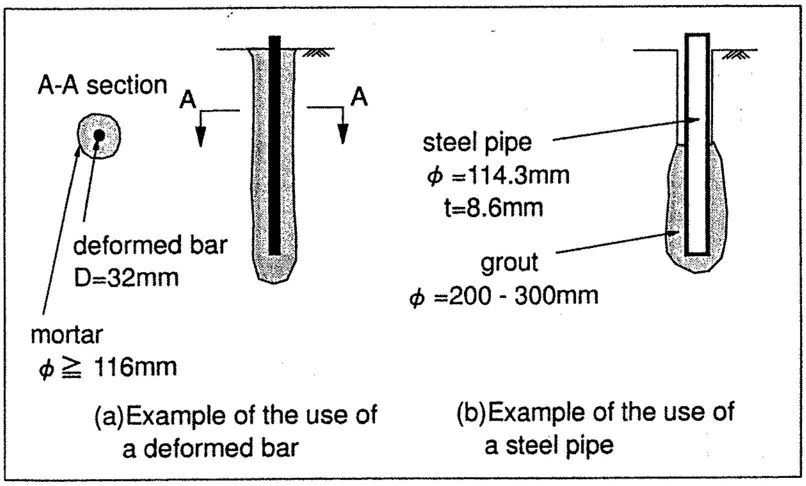
Table 3.Material properties of steel pipe used as micropiles

JIS category			Mechanical properties	
Material code	Standard number	Standard name	Tensile strength (N/mm ^{2})	Yield point (N/mm ^{2})
STK40	JIS G 3444	Carbon steel pipe for normal structural use	more than 400	more than 235
STPG37	JIS G 3454	Carbon steel pipe for pressurized pipe use	more than 370	more than 215

Table 4.Examples of mortar and cement paste mixtures(per 1m ^{3})

	Cement (kg)	Water (kg)	Sand (kg)	Admixtures (kg)
Mortar	800	400	800	4 (140) *
Cement paste	1,200	600	-	4 (140) *

* When the expansion property is to be improved(approx.1.5%expansion)



(a)Example of the use of a deformed bar

(b)Example of the use of a steel pipe

Fig 9.Typical shape of micropiles

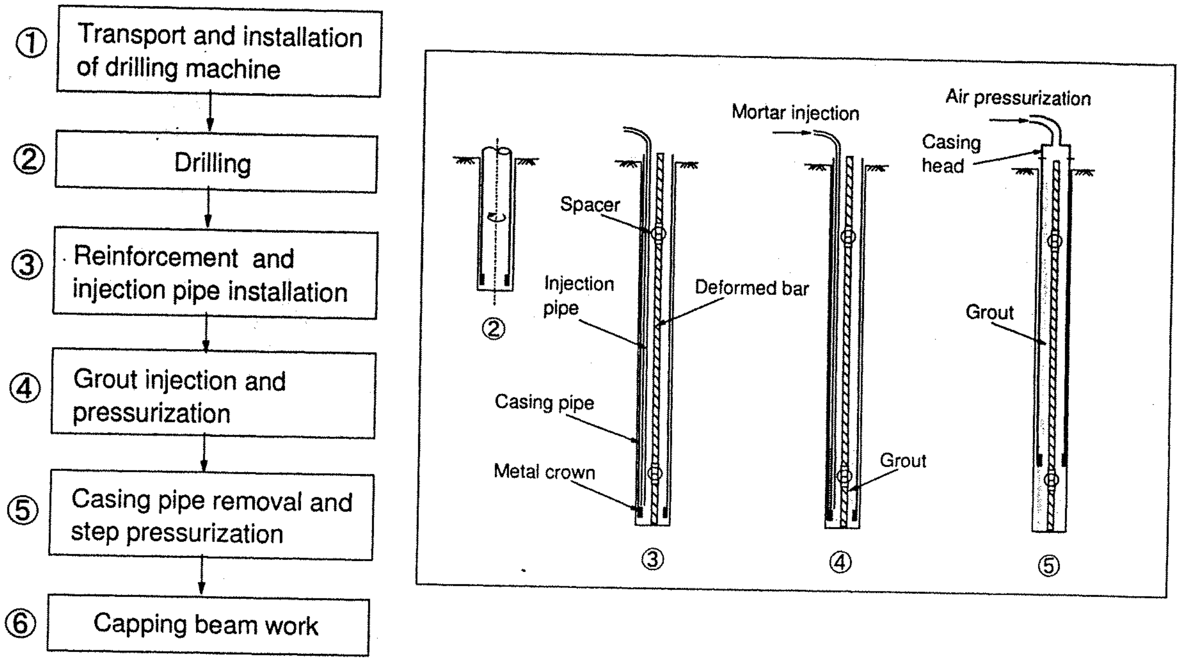


Figure 10.Micropile construction procedure

1.0 and 1.5 m in length.

(2) Installation of Reinforcement and the Grouting Pipe

After the hole has been drilled to the required depth, its interior is thoroughly cleaned with fresh water and the core material and grouting pipe are simultaneously installed down to the bottom of the hole. Spacers are attached to the reinforcing steel at intervals of about 2 m in order to make sure that the covering will be sufficiently thick.

(3) Injection and Pressurization of the Grout

After the reinforcing steel has been placed to the required depth, grout prepared in a high-speed mixer is injected from the bottom of the hole through an injection pipe. Then it is pressurized to 0.5MPa or less depending on the ground condition so that the grout adheres tightly to the natural ground.

(4) Removal of the Casing Pipe and Step Pressurization

After it has been ascertained that the grout is being expelled from the mouth of the casing pipe, the injection pipe is pulled out and a casing head is attached, then as pressurization is performed, the casing is gradually pulled out. At this time, the sinking of the grout surface is observed and supplementary grout injected as necessary. The standard pressurization frequency is once every 2 m.

(5) Capping Beam Work

After the micropile work has been completed, the pile heads are processed at a predetermined location then linked by a capping beam.

4.3 Quality Control Method

Table 5 summarizes quality control items, control methods, and control standard values,for each stage of the process.

5. Future Prospects and Issues

5.1 Future Application Fields and Unresolved Problems

In Japan, most micropiles have been installed as in- situ earth reinforcement measures, with their use as structural reinforcement limited to

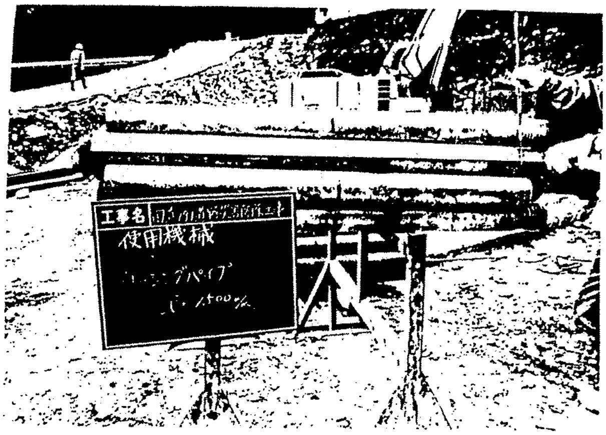


Photo 1.Casing pipe

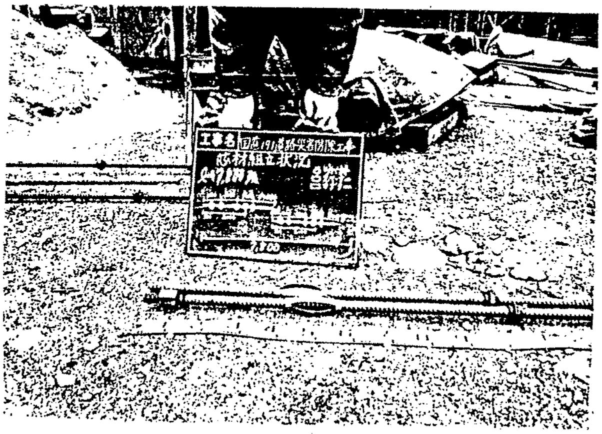


Photo 2.Deformed bar

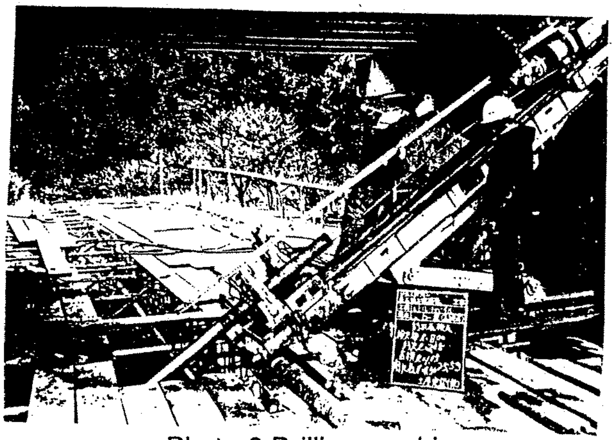


Photo 3.Drilling machine

Photo 4.Grouting pump

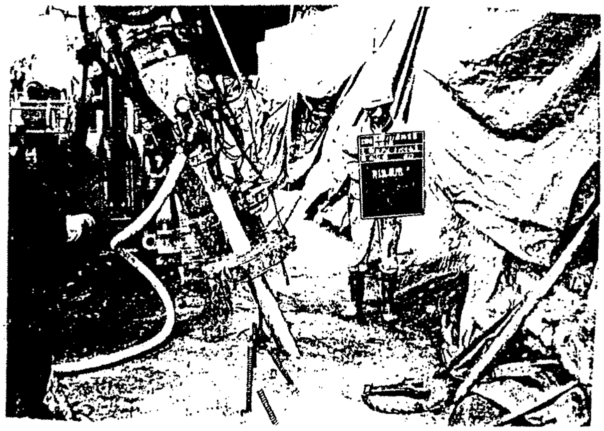


Photo 5.drilling

Photo 6.Mortar injection

Table 5.Micropile quality control items

Process	Control period	Control item	Control details	Standard value	Measurement frequency	Control methods
Drilling	During drilling machine installation	Drilling location	Drilling location	±100mm	All piles	Scale
		Drilling angle	Drilling angle	±2.5degrees	All piles	Slant rule,large ruler
	During drilling	Drilling condition	Speed,Thrust,Rotation torque,etc.		All piles	Control devices
			Slime sampling State of discharge of pressurized water		All piles	Visually
	After drilling	Drilling depth	Hole length	+100mm	All piles	Measuring rod
		Drilling cleanliness	Quantity of residual slime		All piles	Visually
Injection	After mixing	Quality of grout	Quantity of surface water on fine aggregate	Max.Differential: 0.30%	Twice/day	Flask,scale
			Weight of materials	Water, Cement: ±1% Fine aggregate: ±3%	Once/1batch	Scale,water meter
			Consistency(Flow value)	19sec±3sec	Twice/day	P sieve•Astop- watch
			Chloride content	Max. 0.3kg/m3	Once/$10m^3$	Measurment device
			Compressive strength	Design strength or greater	Once/$10m^3$	Unconfined compression test
	During injection	State of grout	Quantity injected		All piles	Flow meter
			Pressurization		All piles	Pressurization system
Installation of reinforcement	Before installation	Quality of reinforcement	Quality of reinforcing steel		All piles	Quality inspection certificate
			Length of reinforcing steel		All piles	Scale
	During installation	State of iastallation	Coupler tightness,Head adjustment		All piles	Torque wrench,scale
Pile load test	After construction	Bearing capacity	Load,Displacement	Completely safe under the design load	In principle, 5% and at least 3 piles	Jack,dial gauge

foundations for small scale structures such as retaining walls and the underpinning of the foundations of existing structures. The use of high capacity micropiles using steel pipe as the reinforcing steel will lead to the use of micropiles in seismic retrofit work on bridge foundations. Before this can be done, design related issues must be resolved: harmonization with the Specification for Highway Bridges , the development of a method of assessing the distribution of the load with the existing foundation, and so on.

The design method of the micropile is characterized by group effect and network effect. In the design of the pile foundations for structures, however, these effects are presently ignored. This is because the diameter of piles for foundations is larger than usual and the behavior of the micropiles is still unknown.

In general, pile foundations for structures shall be checked as follows:

(a)Axial(or Vertical) bearing capacity of the pile
(b)Lateral(or Horizontal) resistance of the pile
(c)Structural design of the pile body
(d)Design of the micropile- footing connection
(e)Structural design of footing

In the case of a micropile, the resistance of the pile is affected by the geotechnical parameters such as grout/soil (or ground) interface conditions. Then, presently the estimation method of the resistance of the micropile in the axial and lateral directions is not prescribed in the Codes or Specifications. Therefore, usually, and especially for the preliminary design, the design method for large bored pile is used in the design of micropile instead. This design method is conservative.

Table 6 shows the comparison of the micropile design method for pile foundations between AASHTO and the Specifications regarding the resistance of the pile in the axial and lateral directions. Here, the pile type is A(Tremie Grouted Micropiles). The estimation of ultimate load in the axial direction is performed by the geotechnical engineering method, such as α - method or β - method in AASHTO, whereas by the empirical method using SPT- N value in the Specifications. And the lateral deflection of the pile(δ_{Ha}) is limited such as δ_{Ha} =0.1D(D=pile diameter) in the Specifications.

Table 6.Geotechnical design guidelines for single piles

Loading	Axial		Lateral	
Purpose	Ultimate Load (Skin Friction)	Movement Control	Ultimate Load	Deflection Control
AASHTO(1992) (Drilled Shafts) (Piles)	α meth-coh-TSA β meth-gran-ESA	Refer to ES,FE	Refer to AS.	Refer to ES,FE,"p-y"
Specifications(1996)* (Bored Piles)	f_{gran}=0.5N (≦0.2MPa) f_{coh}=c or N (≦0.15MPa)	Kv-method	Refer to AS	δ_{Ha}=0.1D Displacement method

*Specifications(1996) : Specifications for Highway Bridges Part Ⅳ(Substructures) (JRA)
TSA : Total Stress Analysis , ESA : Effective Stress Analysis , ES : Elastic Solutions ,
FE : Finite Element , AS : Analytical Solutions , "p-y" : P-y curves ,
f : Ulitimate unit skin friction , N : SPT-N value , c : cohesion of the soil ,
Kv : Spring constant at pile top , δ_{Ha} : Allowable horizontal deflection , D : Pile diameter

The following are Japanese subjects on the micropile in the future.

(a)Relation between the effect of the grout in each pile type and its geotechnical resistance of the pile shall be clear and prescribed as the estimation method of the pile resistance in the Specifications.

(b)The limit state design shall be introduced in the Specifications near future. Then, it will be expected that the movement or deflection of the pile is estimated with high accuracy. Load-deflection(or movement) behavior of the micropile shall be clear for the design.

Small diameter steel pipe which can be used as high strength micropiles is not distributed on the market and cost issues related to the acquisition of materials, improvement of construction machinery, etc. must be studied.

To promote the increased use of this method to construct simple foundations for new small scale structures such as retaining walls, it must be distinguished from other methods (normal small diameter piles already used), and it would be beneficial to develop a rational design method which accounts for one of the strong points of the micropile method, namely its group effect and network effect. But while it has been reported that experiments have verified that it actually provides the group and network effects, this has not been corroborated theoretically, so further study is necessary to do so.

5.2 Proposed New Quality Control Methods

(1) Integrity Test

Because it is impossible to directly confirm the shape of the grout around a micropile from above ground, it must be inspected using a non- destructive method. A study was performed to determine the usability of the integrity test, one used for quality control of cast in- situ piles, as a way to perform this confirmation.

As shown in Figure 11, an integrity test is done by placing a sensor near the center of the top of a pile to measure the acceleration when the pile is tapped with a small hammer. Generally, under a slight force, a pile tip becomes a free end, producing a reflected wave with the same components as the vibration speed input at the pile head. The time required for the reflected wave to return after the pile top is impacted is equal to the time required for the wave to travel both ways through the pile once, and if the wave velocity is known, it is possible to estimate the pile length.

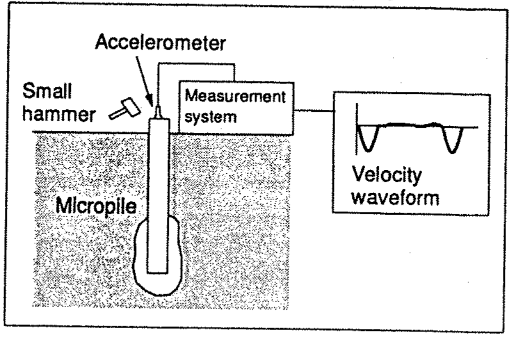


Figure 11.Integrity test method

This velocity varies according to the quality of the pile, and is usually a value within the range shown in Table 7. And if there is a change in the cross section area along the length of a pile, this also produces a reflected wave. This permits an estimation of the shape of the pile because if the cross section area widen, a reflected wave with a velocity which has the reverse sign against the input wave is generated, and if the cross section area narrows, a reflected wave with a velocity which has the identical sign against the input wave is generated.

Table 7.Wave velocity

Type of piles	Wave velocity (m/sec)
Cast in- situ pile	3,800 - 4,000
Precast concrete pile	4,000 - 4,300
Steel pipe pile	5,000 - 5,200

Figure 13 shows the measured wave forms obtained during integrity testing of the RC pile shown in Figure 12: a pile with an enlarged base at its end, a diameter of 30 cm, and a length of 4.0 m. In the figure, the horizontal axis represents the pile length and the vertical axis represents the velocity, and the first downward peak represents input from a plastic hammer. Peaks considered to represent the wave reflected from the enlarged base and the wave reflected from the tip of the pile can be clearly observed. These results reveal that it is possible to measure clear fluctuations in a pile's cross section using integrity testing. But because the results were obtained under uniform ground conditions created inside a soil tank, at actual work sites, it would be necessary to consider the effect of the ground. Before integrity testing is used with micropiles, its usability will be clarified by additional laboratory experiments and in- situ testing in order to answer various questions. How many wave velocities will be set for a micropile, which is a compound body consisting of steel pipe, grout, and steel reinforcing rods? To what extent will it be possible to measure gentle changes in grout shape? In Europe where integrity testing has come into wide use, its application is positioned as a temporary survey method; a number of piles are tested to detect defective piles based on a relative assessment of the wave forms. Consideration will be given to introducing the method for use in this way.

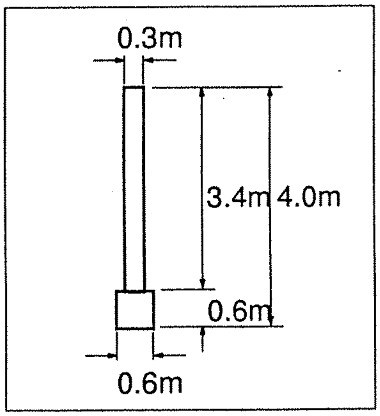


Figure 12.Shape of the test pile

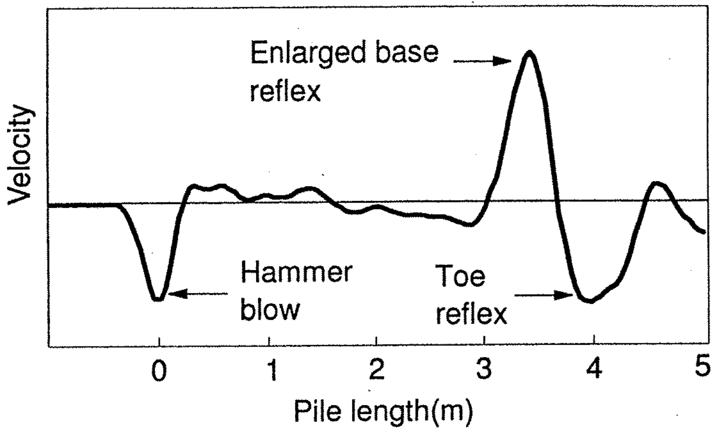


Figure 13.Measured wave forms obtained from integrity test

Photo 7.Performance of integrity test

(2) Statnamic Load Testing

Static load testing is considered to be the most reliable way to confirm the bearing capacity of a pile. But because static load testing is both extremely expensive and time- consuming, it is actually only performed for important structures. However, dynamic load testing and statnamic load testing, which provide the advantages of low cost and speed, are being applied with increasing frequency. The performance of many tests of this kind can clarify the distribution of bearing capacity throughout an entire foundation, contributing to improved safety. Assuming that high capacity micropiles will be used frequently in the future, it is believed that it will be possible to use the statnamic load testing method to perform simple confirmations of bearing capacity, resulting in greater reliability.

Statnamic load testing was developed by devising a loading method that does not apply a sudden force to piles, and which drives piles at a loading time of about 0.1 seconds. As shown in Figure 14, gas pressure produced by burning a propellant lifts a reaction mass upwards, and its reaction acts on the pile head as a load. In addition to Japan, it has been used extensively in Europe, Canada, the United States, and in Asian countries. Because this test can be done without a pile driver or reaction pile, and requires only specially designed loading equipment that can be prepared quickly, it is possible to choose any convenient time to perform the test. But because the loading time is much shorter than that of static loading, the effects of the acceleration and velocity have to be removed from the test results to obtain the static resistance.

Figure 15 presents load - displacement relationships obtained from static load testing and statnamic load testing of a steel pipe pile with an external diameter of 400 mm and a length of 13 m. In the statnamic load test case, it was assumed that the pile length was 13 m and that it was a rigid body, and the unloading point method was used to calculate the static resistance without the rate effect. A comparison reveals that the initial gradient was identical for the two cases. A difference of about 20% appeared between their static resistance values, but this was not caused by an underestimation of the static resistance by the statnamic load test; it was a result of an increase in the penetration depth and the action of the closing effect at the tip, both caused by

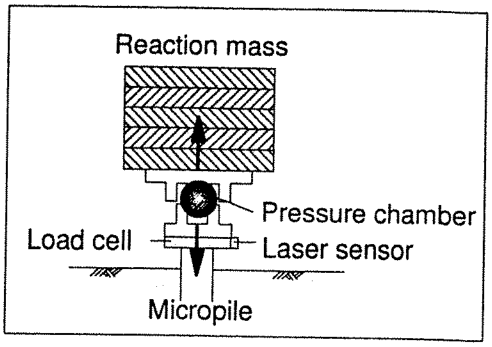


Figure 14.Statnamic loading principle

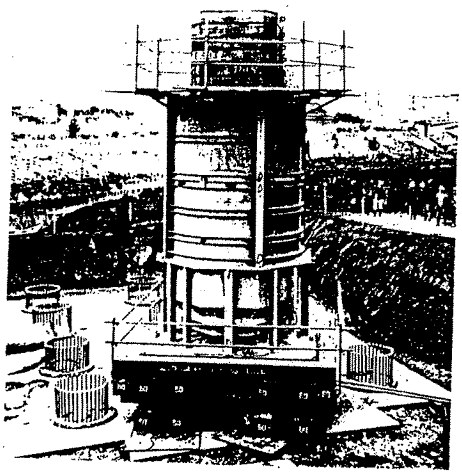


Photo 8.Performance of Statnamic test

cyclic testing of the same pile. And Figure 16 presents a comparison of the axial force distributions obtained from the static load testing and the statnamic load testing, showing that the distributions in the two cases conform closely and that statnamic load testing can confirm loading properties which are nearly static without generating tension waves. Consequently, it is possible to reproduce the loaddisplacement relationship which would be obtained by static load testing with extreme accuracy by deducting the rate effect from the statnamic test results. Based on past examples, the static bearing capacity is estimated with an error between 10% and 20%.

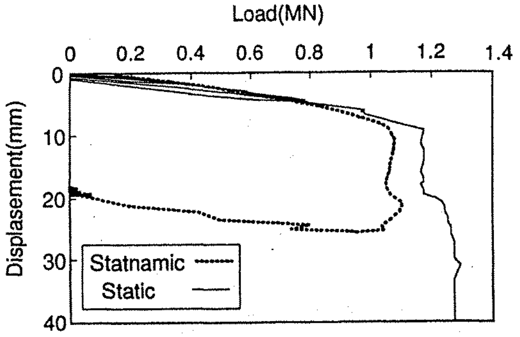


Figure 15.Example of comparison of loaddisplacement relationships(Steel pipe pile,D=400mm,L=13m)

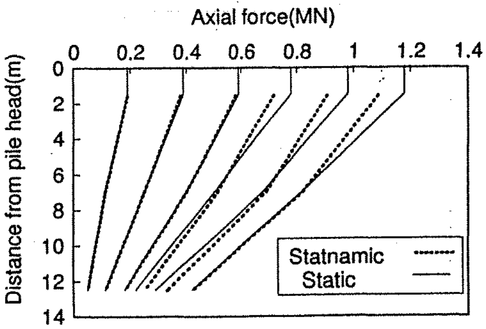


Figure 16.Example of comparison of axial force distributions
(Steel pipe pile ,D=400mm ,L=13m)

Both integrity testing and statnamic load testing will be performed with full size micropiles to quantitatively assess the suitability of the two test methods.

Acknowledgments

In conclusion, the authors wish to express their gratitude to Mr. Otani of Hirose Co.,Ltd., who provided data concerning past micropile constructions and Mr.Matsui of CTI Engineering Co.,Ltd.,who provided useful suggestions about design methods of micropiles.

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