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Development and Commercialization of Gantetsu Composite Foundation Pile

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Abstract

Due largely to the Noise Regulation Law and the Vibration Regulation Law, the conventional percussion pile driving method has almost been impossible to adopt in urban areas. Nippon Steel has developed a low-noise and low-vibration pile driving method named Gantetsu pile. It is highly earthquake-resistance and causes less damage to the environment than conventional pile driving methods. The ground soil is mixed with cement milk to form a soil cement column, into which a pile with an embossed exterior is driven to form a steel and soil cement composite pile. In order to commercialize Gantetsu pile, new technologies have been synthesized. This paper describes the social needs and details of the Gantetsu pile.

1. Introduction

Gantetsu piles have been developed to reduce the volume of construction-generated surplus soil and lessen the environmental impact, develop steel pipe piles that are more cost competitive than cast-in-place piles, and enhance the seismic performance of foundations in the wake of the Hanshin-Awaji Earthquake of January 1995.

The start of the urban construction boom in 1988 and the shortage of industrial waste disposal sites led to a demand for methods to sharply reduce the volume of construction-generated surplus soil. The subsequent collapse of the bubble economy temporarily diminished the demand, but reducing the amount of surplus construction soil was a problem inseparable from mounting environmental considerations, especially in urban areas.

Later, the tightening regulations on noise and vibration made it impossible to apply in urban areas the hammer driving method, a conventional steel pipe installation method with high construction cost competitiveness. This allowed the cast-in-place pile method with low vibration and noise features to find rapidly increasing usage. The inner-excavation steel pipe pile method with similarly low vibration and noise was then developed. Consisting of drilling a hole in the ground at a diameter slightly larger than that of a steel pipe pile and installing the steel pipe pile into the bored hole, this method decreased the designed skin frictional force and increased the number of structural piles required for pile-withdrawing load in an earthquake, thereby increasing the construction cost relative to the cast-in-place pile method. There developed a demand for a new pile installation method with low vibration and noise characteristics.

Most recently, the Hanshin-Awaji Earthquake of January 1995 destroyed many structures or rendered many structures unusable. One of the causes was the inadequate foundation seismic resistance requirements and this led to the review of seismic design methods. In addition to the conventional seismic coefficient method, a new method was established based on ultimate lateral strength in an earthquake. The seismic coefficient method grasps the structural members and ground over a linear range, with respect to a seismic force of 0.2 G (the horizontal force in an earthquake is assumed to be 0.2 times the vertical force), and designs the foundation by limiting soil resistance, member stress and foundation displacement to levels smaller than allowable values. The ultimate lateral strength method assumes that the energy of an earthquake is absorbed by the deformation of piers at seismic forces of 1.0 and 2.0 G, and designs the foundation so that

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the yield strength of the foundation analytically determined by considering the nonlinear characteristics of the ground and members exceeds the yield strength of the piers. That is, the concept of positively evaluating the load-bearing capacity and deformation performance of the foundation was introduced into the design of the foundation, opening the way for a positive evaluation of the seismic performance of composite piles like the new Gantetsu piles.

The Gantetsu pile method makes effective use of the soil at the site to reduce the amount of construction-generated surplus soil and not to loosen the ground. The steel pipe pile with an embossed exterior can deliver a supporting capacity equivalent to that of a cast-in-place pile that is 20 to 30% larger in diameter, thereby reducing the construction cost. High seismic performance is achieved by the combined effect of the steel pipe and the soil cement within it. The technical elements, cost competitiveness, seismic performance, application results, and future prospects for the Gantetsu piles are described below.

2. Technical Elements

2.1 Pipe specifications

2.1.1 Pile classification

The Gantetsu pile is schematically illustrated in **Fig. 1**. Cement milk is injected into the ground and agitated to form a soil cement column. Simultaneously, a steel pipe with outside surface projections is rotated into the soil cement column to build a soil cement-steel pipe composite pile. **Photo 1** shows the end of a Gantetsu pile that was excavated and sectioned. The steel pipe diameter is 1,000 mm, and the soil cement column diameter is 1,400 mm. The Gantetsu pile is able to form a strong concrete-like end in gravel.

The Japan Society of Civil Engineers classifies the Gantetsu pile as a steel pipe pile with an embossed exterior according to the construction material, and as a bored pile according to the installation method. The steel pipes used for the Gantetsu pile method range from 600 to 1,200 mm in diameter and are in the medium-diameter region for steel pipe piles class.

2.1.2 Steel pipe with outside surface projections

The Gantetsu pipe consists of steel pipe with outside surface projections. This steel pipe is produced by a spiral pipe forming process from a steel strip with 2.5 mm or higher projections rolled at intervals of 40 mm or less. **Fig. 2** schematically illustrates the steel strip used to produce the surface with projection and the process for manufacturing the steel pipe from the steel strip. The outside projections are trapezoidal in shape and have an average cross-sectional area equivalent to that of a 0.5 mm or thicker strip. The shape of the steel pipe's surface projection and the strength of the soil cement column are determined, so that the bonding force between the steel pipe and the soil cement column becomes greater than the friction transfer force between the soil cement column and the ground.

The spiral angle between the projections and the axial direction of the steel pipe is a maximum 40 deg. considering the transfer of forces in the axial direction of the steel pipe. The steel pipes meet the specifications of JIS A 5525, Steel Pipe Piles. The steel strip with projection is manufactured at a rate of 20,000 tons per year. Increasing production is enhancing the product yield and improving the spiral pipe forming mechanism.

2.2 Development of new construction method

2.2.1 Establishment of high-efficiency, high-quality, and environmentally friendly construction system

The development of the new method was targeted so that compared with competing cast-in-place piles it would be capable of in-

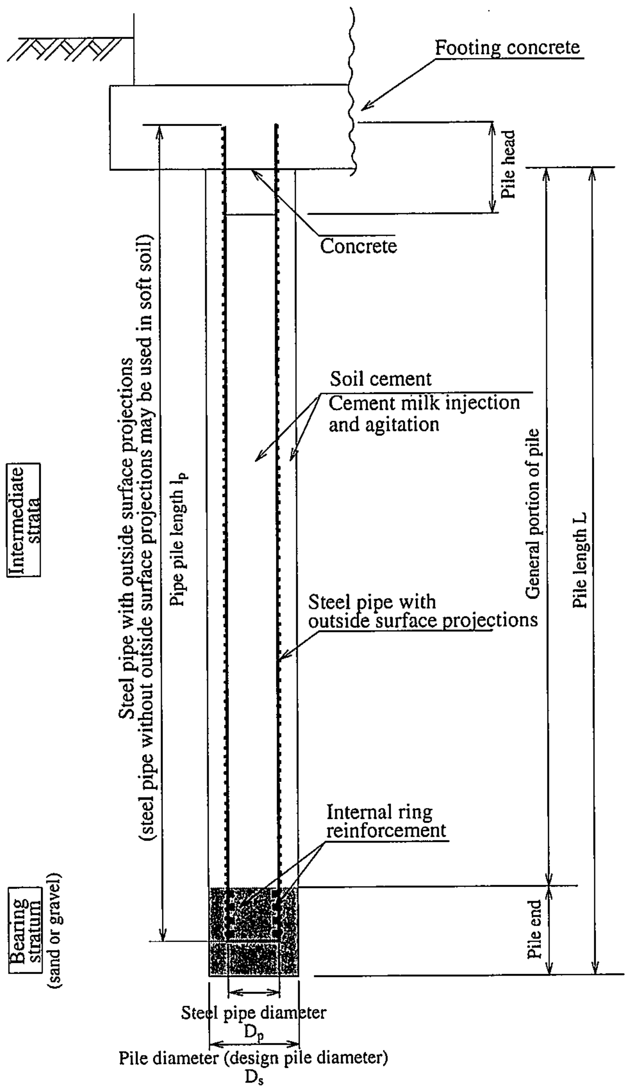


Fig. 1 Schematic illustration of Gantetsu pile

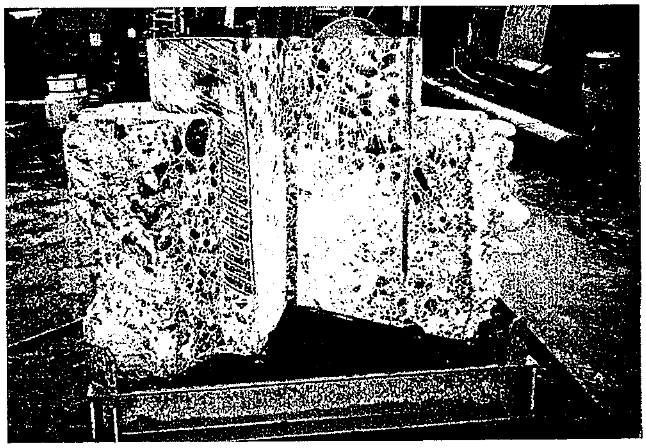


Photo 1 End of Gantetsu pile formed in gravel
Gantetsu pile constructed on site was excavated, cut, and photographed

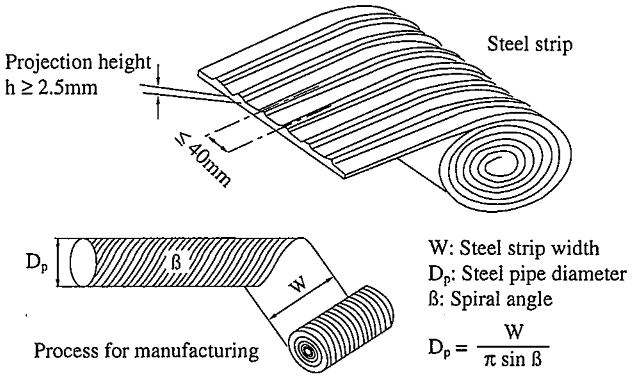


Fig. 2 Steel strip for steel pipe with outside surface projections and process for manufacturing steel pipe with outside surface projections

stalling steel pipe piles of a smaller diameter with a larger bearing capacity, at higher efficiency and lower vibration and noise without loosening the surrounding soil. From among deep mixing methods for soil stabilization, the Teno-Column method of Tenox Corporation was selected as it could form soil cement columns of high quality with a simple mechanism. Based on the Teno-Column method, a simultaneous burial method was developed to complete the formation of the soil cement column and the installation of the embossed steel pipe in one operation. The Gantetsu pile construction process is shown in **Fig. 3**. The Gantetsu pipe method is the world's first of its kind, and five patents and five utility models have been registered.

The noise and vibration levels of the Gantetsu pipe method are shown in **Fig. 4**. The new method fully meets the vibration and noise standards, and produces much lower vibration and noise than the competing methods.

The construction control system of the Gantetsu pile method is shown in **Fig. 5**. The Gantetsu pile construction machine, cement milk mixing plant, and site control room pile monitor communicate with each other by radio. Design data, such as the estimated ground map, penetration rate and cement milk injection rate, are compared with real-time actual data like rod penetration resistance, and are controlled accordingly. The construction control system can confirm the arrival of all pipes at the desired bearing stratum as shown in **Fig. 6**, thereby assuring the quality of the piles. This system is unique to the Gantetsu pile method and is the most advanced in the industry. The simultaneous burial method and the construction control system enables long Gantetsu piles to be installed with certainty. The maximum length of Gantetsu piles with 1,000-mm diameter (steel pipe diameter of 800 mm) that have been installed to date is 67 m.

2.2.2 Establishment of construction conditions to meet both of low soil discharge rate and easy construction

A key point of the Gantetsu pile method was to reduce the volume of soil discharged from the site by making effective use of soil at the site. When cement milk is injected into the ground and agitated to build a soil cement column, the proportioning of the cement milk has a large impact on the steel pile penetration and the soil discharge volume. Generally when the water-cement ratio is raised to increase the unit water content, the soil cement density drops and facilitates the steel pipe penetration, but conversely the soil cement strength decreases and the soil discharge rate increases. The results of construction tests conducted in a variety of soils indicate that a proportional mix using 300 kg of cement and a water-cement ratio of 100% for 1 m^3 of site soil can meet both assure the steel pipe pen-

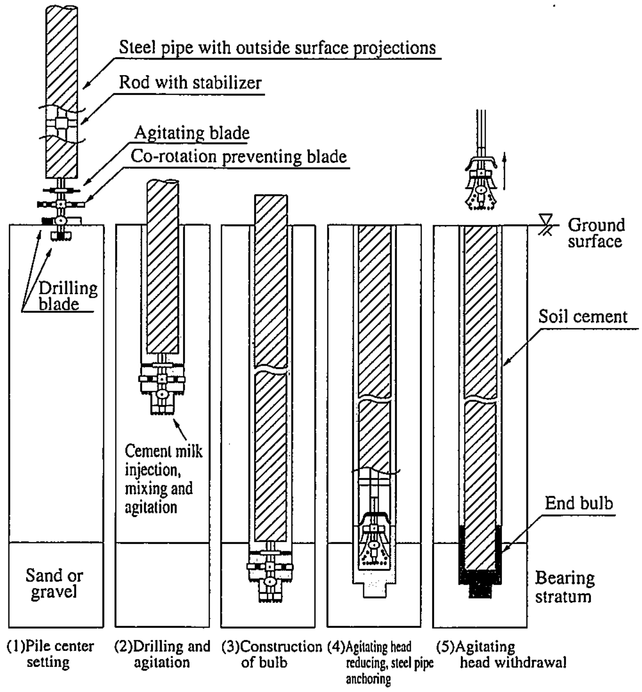


Fig. 3 Gantetsu pile construction procedure

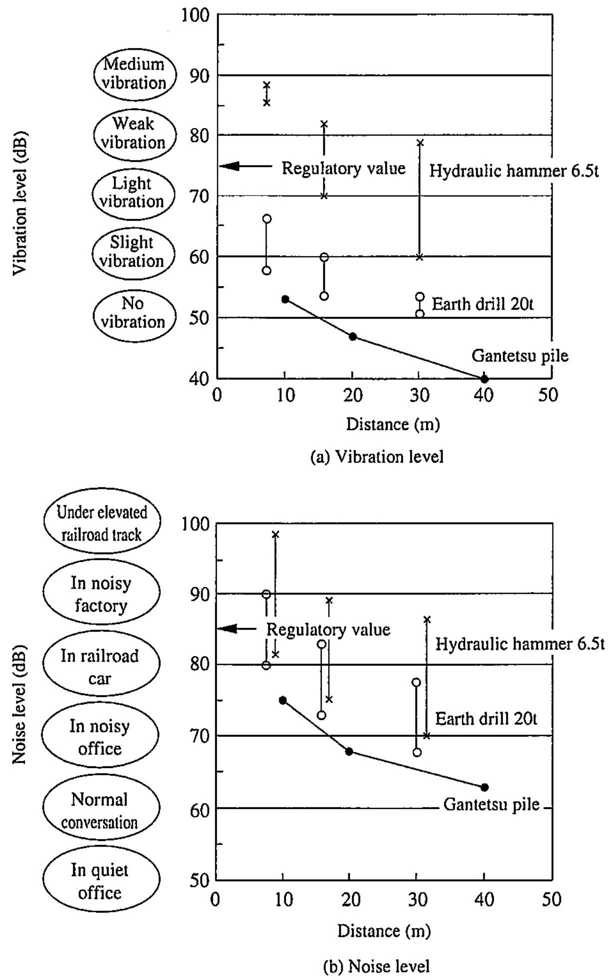


Fig. 4 Vibration and noise levels during Gantetsu pipe construction

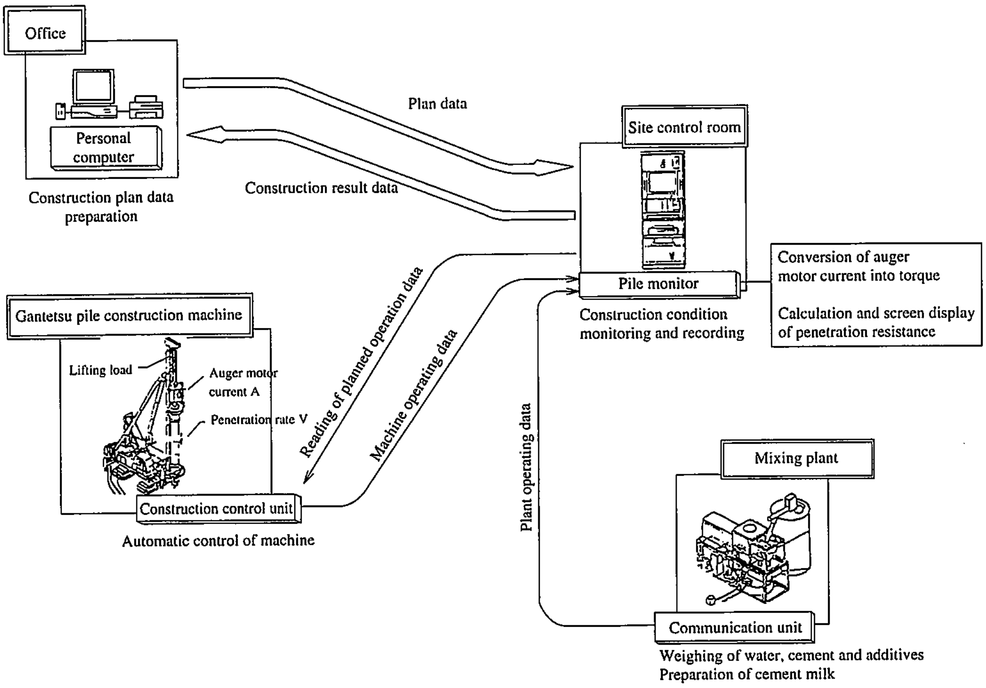


Fig. 5 Gantetsu pile construction control system

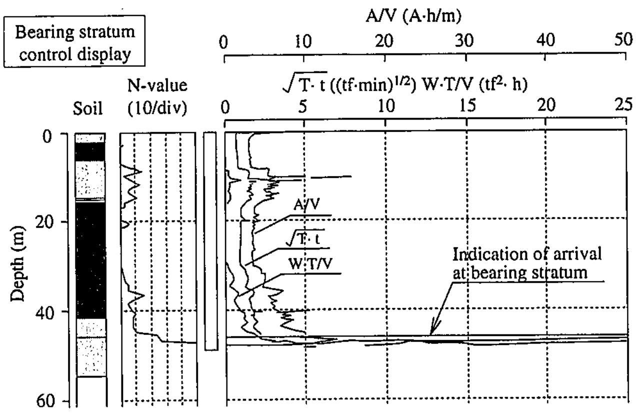


Fig. 6 Example of bearing stratum arrival control according to penetration resistance

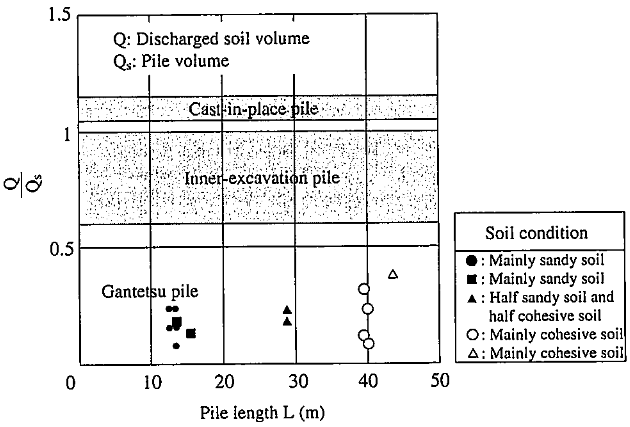


Fig. 7 Relationship between discharged soil volume/pile volume ratio and pile length

etration and reduce the soil discharge rate. The volume of soil discharged for the Gantetsu piles was 20 to 40% of the pile volume on average and was a half to one-fifth of that of other types of piles of the same diameter as shown in **Fig. 7**. With growing environmental awareness in recent years, this reduction in the volume of construction-generated surplus soil has becoming a big selling point for the Gantetsu pile method.

2.3 Design method that reflects performance

2.3.1 Large bearing capacity without soil loosening

The Gantetsu pile method required some design considerations to increase its competitiveness over rival pile foundation methods. Since existing design methods could not be applied to the new Gantetsu pile concept, a design method was developed to take advantage of the actual performance of the Gantetsu pile as much as possible.

First, the mechanism by which the Gantetsu pile delivers its large bearing capacity was studied. The unit weight of soil cement for the Gantetsu pile is about 1.7 to 1.8 g/cm^3 on average and is practically the same as the specific gravity of the site soil. This acts as liquid pressure on the soil surrounding the soil cement column as shown in **Fig. 8**. The liquid pressure, which is greater than the resting earth pressure, was expected to prevent the soil from being loosened by the penetration of the steel pipe pile.

To demonstrate this mechanism, measurements[1] and numerical analyses by FEM and other methods[2] were carried out. A lateral pressure measuring device, called a geocell[3], was buried in the bearing stratum at a horizontal point equivalent to the pile diameter away from the pile center and at the same depth as the end of the pile, as shown in **Fig. 9**. The change in the earth pressure with the installation of the Gantetsu pile was measured with the geocell. The measurement results are shown in **Fig. 10**. When the drilling and agitating head advanced to GL–11 m or short of the bearing stratum, the earth

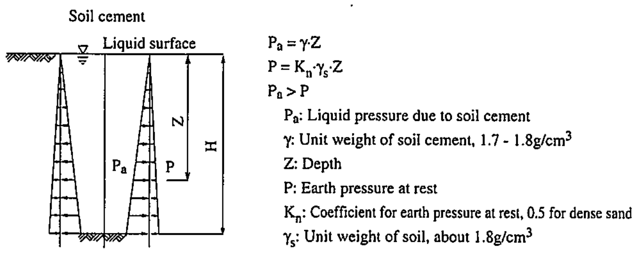


Fig. 8 Schematic illustration of liquid pressure action of Gantetsu pile

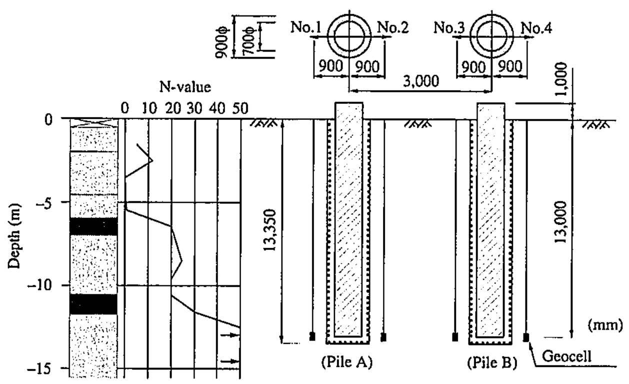


Fig. 9 Gantetsu pile penetration depth and geocell installation

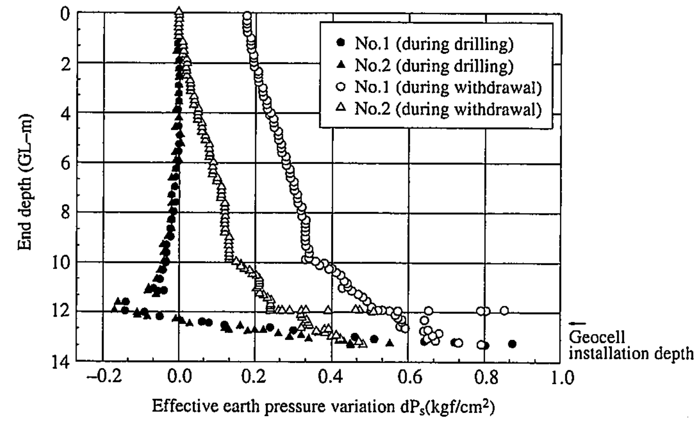


Fig. 10 Changes in drilling head depth and lateral pressure for Gantetsu pile B

pressure in the bearing stratum at GL–13 m changed little. The earth pressure slightly decreased as the drilling and agitating head penetrated deeper, and increased when the drilling and agitating head entered the bearing stratum. The earth pressure slowly decreased when drilling stopped and after the withdrawal of the drilling and agitating head, and remained higher than that before the installation of the Gantetsu pile. This suggested that the soil was not loosened.

The bearing performance of the Gantetsu pile was finally evaluated by full-scale loading test. The design bearing capacity of the end of the Gantetsu pile was a maximum of 750 tf/m^2 in sand and a maximum of 1,000 tf/m^2 in gravel, and this was 2.5 to 3 times greater than the 300 tf/m^2 for cast-in-place piles.

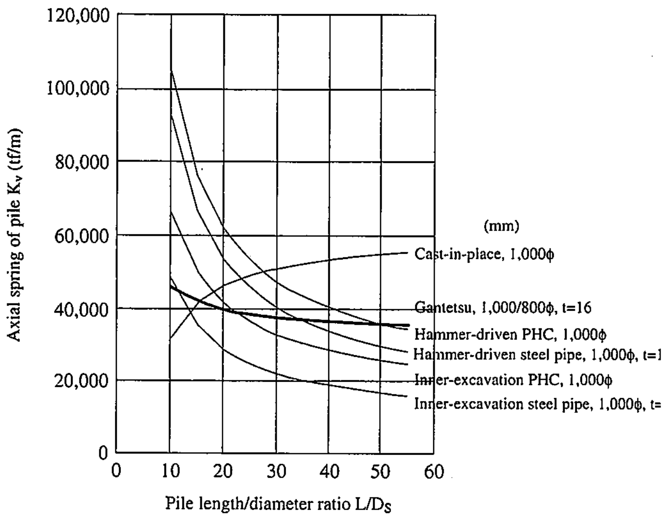


Fig. 11 Relationship between axial spring of pile and pile length/diameter ratio

2.3.2 Axial spring of stiff pile by combination of steel pipe and soil cement

A Gantetsu pile installed without loosening the surrounding soil and constructed with an integral steel pipe and soil cement column has a stiffer spring in the axial direction than that provided by other steel pipe pile methods. **Fig. 11** shows the relationship between the axial spring K_v and the pile length/pile diameter ratio L/D_s for various piles of the same diameter. The K_v values of the Gantetsu piles were derived from the results of 15 loading tests, including those by similar methods. When designing 1-m diameter 30-m long piles by assuming a pile-head steel plate thickness of 16 mm, the K_v value of the Gantetsu piles is about 80% of that for cast-in-place piles and 170% of that for inner-excavation steel pipe piles. Generally, steel pipe piles have less stiffness than that provided by competing methods and displace more when subjected to large inertial forces in an earthquake. For these reasons, they were disadvantageous for use in viaducts and other foundations where their allowable design displacement was limited. The Gantetsu piles achieved high stiffness by the integration of the soil cement column with the steel pipe, making them more functionally competitive than cast-in-place piles.

3. Seismic Performance

3.1 Evaluation of seismic performance by horizontal alternating load test

Gantetsu pile members were subjected to horizontal alternating load testing under constant axial force to evaluate their load-bearing performance and deformation performance and to reflect the results in their design[4)]. The parameters of the specimens are given in **Table 1**, and the testing apparatus is illustrated in **Fig. 12**. The test parameters were established to evaluate the effect of the embossed exterior, the combined effect of the soil cement in the steel pipe and the steel pipe, and the effect of the strength of the soil cement. An alternating load was quasi-statically applied to the specimen at right angles under a constant axial force of 120 tf (30% of the yield load specified for the steel pipe). The loading pattern is shown in **Fig. 13**. The horizontal displacement δ_{yd} with respect to the design yield stress (σ_{yd} = 2,400 kgf/cm^2) was obtained by load control. Fully-reversed alternate loading was performed in three cycles over the amplitude δ_{yd}. The amplitude was then increased by integral multiples of δ_{yd}.

Table 1 Parameters of specimens

Specimen	Specification	Soil cement strength (kgf/cm²)	Steel pipe diameter (mm)	Wall thickness (mm)	Yield point of steel pipe (kgf/cm²)	Standard of steel pipe
Case 1	Ordinary steel pipe	Without soil cement	600	9.07	3,150	SKK400
GR-1	Steel pipe with outside surface projections	Without soil cement	600	9.02	3,330	SKK400GR
GR-2	Steel pipe with outside surface projections + Soil cement	57	600	9.02	3,330	SKK400GR
GR-3	Steel pipe with outside surface projections + Soil cement	28	600	8.70	3,330	SKK400GR

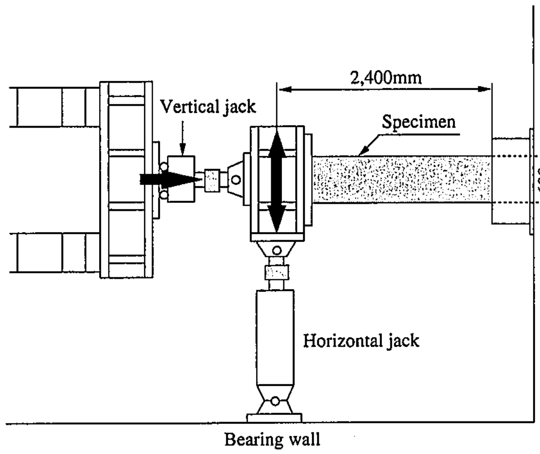


Fig. 12 Schematic illustration of horizontal alternating load testing apparatus

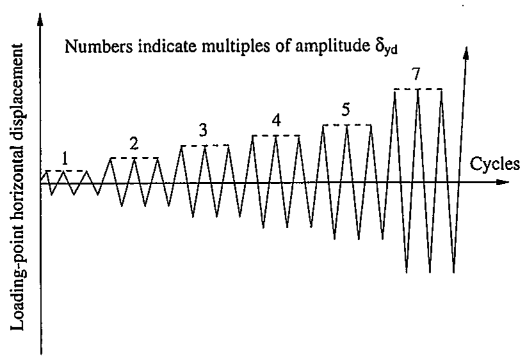


Fig. 13 Loading pattern for horizontal alternating load test

The test was continued until the maximum load in each cycle exceeded the yield load or the specimen clearly reached its ultimate design limits due to buckling of the steel pipe, for example.

3.2 Results of alternating load test

Load-displacement envelopes are shown in **Fig. 14**. The load and displacement in this figure are made dimensionless by the yield load P_y calculated from the actual yield point of the steel pipe and by the corresponding yield-point displacement σ_y, respectively. Comparison of the specimens produced the following findings about the maximum load-bearing capacity and deformation performance of the Gantetsu pile. (1) Steel pipe with outside surface projections has maximum load-bearing capacity and deformation performance improved by its embossed exterior surface compared with ordinary steel pipes of the same wall thickness. (2) Load-bearing capacity and deformation performance of the Gantetsu pile are improved by the combined effect of the steel pipe and the soil cement in the steel pipe, and these improvements increase with increasing soil cement strength.

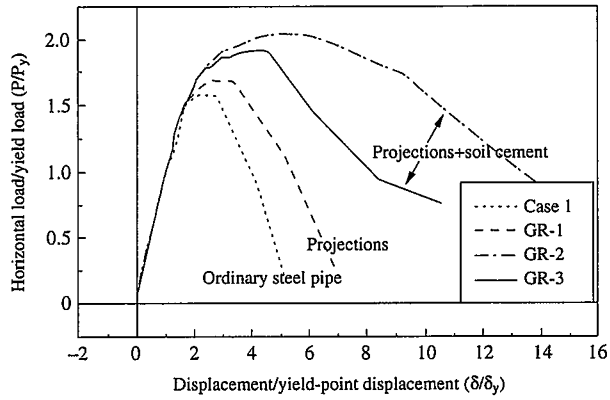


Fig. 14 Nondimensional load-deformation envelopes (actual yield point)

3.3 Reflection of seismic performance in design

As shown in **Table 2**, the standard design method evaluates the combined effect of only the horizontal subgrade reaction coefficient, axial spring, and bearing capacity. The axial force and bending of the pile are designed for the steel pipe alone. This is not the design of a composite pile, in the true sense of the term, because it assumes that the uniaxial compressive strength of the soil cement is a low 10 kgf/cm² and that the contribution of the soil cement to the flexural rigidity of a 1,000-mm diameter pile is a few percentage points at most. As can be seen from the previously mentioned alternating load test results, however, the soil cement in the steel pipe is confined by the steel pipe, so that it clearly contributes to an improvement in the load-bearing capacity and deformation performance of the pile. The actual on-site strength of the soil cement is about 20 kgf/cm².

When the combined effect of the soil cement in the steel pipe and the steel pipe was evaluated by assuming the steel pipe to be a reinforcement of the same cross-sectional area and the Gantetsu pile to be a reinforced concrete pile, the evaluation was found to be on the conservative side. When its strength is 20 kgf/cm², the soil cement translates into an increase of about 1 mm in the steel pipe wall thickness when combined with the total area effect of the exterior embossing. Attempts have already begun to reduce the construction cost of the Gantetsu pile by reflecting this combined effect in its design[5]. We will continue our study to reflect the high seismic performance of the steel pipe-soil cement composite pile adequately in foundation design.

Table 2 Standard design method and seismic performance evaluation method for Gantetsu piles

	Standard design method	Combined effect evaluation method (seismic performance evaluation)
Horizontal subgrade reaction coefficient K_h	Design pile diameter: Soil cement column diameter	Design pile diameter: Soil cement column diameter
Axial spring K_v	Combination of steel pipe and soil cement	Combination of steel pipe and soil cement
Bearing capacity evaluation	Skin friction: OD of soil cement column End bearing capacity: Cross-sectional area of soil cement column	Skin friction: OD of soil cement column End bearing capacity: Cross-sectional area of soil cement column
Axial force and bend calculation	For steel pipe alone	Combined effect of soil cement in steel pipe and steel pipe is converted to corresponding steel pipe wall thickness and added

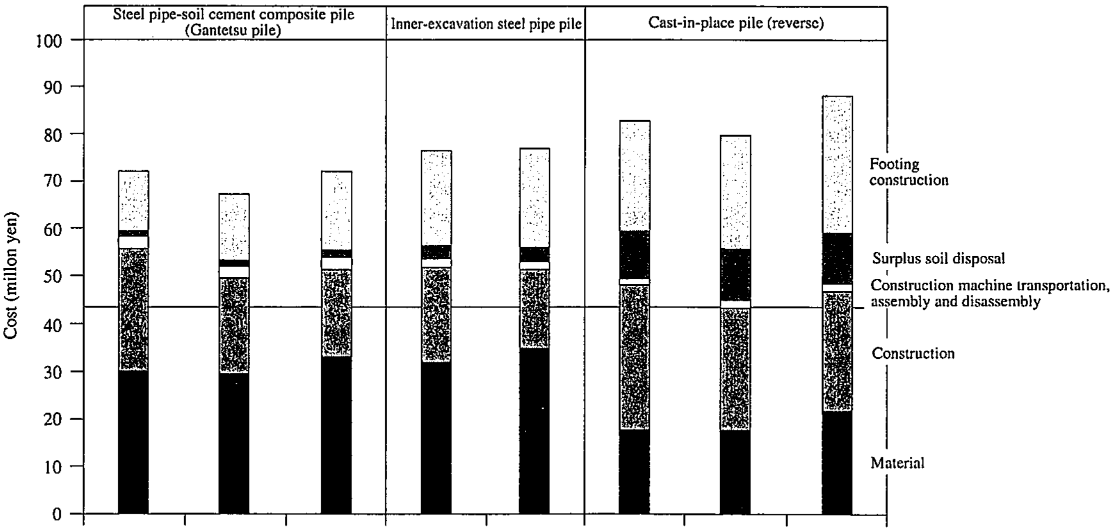
4. Construction Cost

An example of the economy of the Gantetsu pile in comparison with other types of piles is shown in **Fig. 15**. A foundation for a 50-m span elevated bridge with piles installed through soft soil to a depth of 25 m in a bearing stratum was designed and studied for three comparative applications: the Gantetsu piles, inner-excavation steel pipe piles, and cast-in-place piles. The forces were assumed to act at the bottom end of each pier for all three types of piles. The difference in the size of the footing with the diameter and number of piles was reflected in the design of the foundations. The pile materials cost, pile construction cost, construction equipment transportation, assembly and disassembly cost, surplus soil disposal cost, and footing construction cost are cumulatively shown in the figure. The total pile materials and construction costs is smallest for cast-in-place piles of 1,200-mm diameter. The total footing and pile construction costs is smallest for Gantetsu piles of 1,000-mm diameter. These results show that the Gantetsu piles are expensive when considered as individual piles but are effective in reducing the overall construction cost of the foundation structural system.

The number of piles per foundation is almost the same for the 1,000-mm diameter Gantetsu piles and 1,500-mm diameter cast-in-place piles. Under the ground conditions studied, the large bearing capacity of the Gantetsu piles allows the required pile diameter to be reduced by one-third. The pile diameter ratio and pile volume ratio of the Gantetsu piles to the cast-in-place piles in this case are 0.67 and 0.45, respectively. Since the amount of soil removed is about 20 to 40% of the pile volume, the Gantetsu piles can reduce the amount of soil removed per pier by about 90% compared with the cast-in-place piles.

5. Application Results

The use of Gantetsu piles are rapidly growing in civil engineering applications with the establishment of their design methods. The application examples and reasons are given in **Table 3**. The Gantetsu piles are being adopted for such reasons as not only lower construction cost, but also reduced vibration and noise, and less surplus soil generation. **Photos 2 to 6** show the Gantetsu piles used in the construction of the New Meishin Expressway. **Photo 7** shows a high-rise apartment complex built using the Gantetsu piles. The Gantetsu piles used in these and other projects to date range from 900 to 1,500 mm in diameter and up to 66 m in length (for a pile diameter of 1,000 mm and a steel pipe diameter of 800 mm). As of June 1998, Gantetsu piles have been used at 9,000 tons for nine civil engineering projects and at 16,000 tons for 24 building projects. They are expected to be used at an annual rate of 15,000 tons after fiscal 1998.



Pile diameter (mm)	800	1,000	1,200	800	1,000	1,000	1,200	1,500
Steel pipe diameter (mm)	600	800	1,000	800	1,000	-	-	-
Number of piles	42	30	25	63	42	49	36	28
Construction period (days)	25	19	17	34	26	47	48	48

(Soft ground, Pile length: 25m, Force active at lower end of pier: Vertical direction=5 500tf, Horizontal direction=1 500tf, Moment=4 000tf·m)

Fig. 15 Example of economic study for Gantetsu piles

Table 3 Gantetsu pile application examples and reasons

Application area	Foundation type	Application example	Application reason
Civil engineering	Elevated bridge foundation	Elevated bridge foundation for New Meishin Expressway Bridge pier foundation for Aoya Hawai Highway 6 other projects	Low vibration and noise Low cost
	Water treatment plant foundation	Ishinomaki Water Purification Center	Construction without auxiliary method in presence of confined groundwater
Building construction (reference)	Building foundation	Apartment buildings constructed by Housing and Urban Development Corporation Hospitals and post office buildings constructed by Ministry of Posts and Telecommunications Multilevel parking garages 24 other projects	Low soil discharge rate Low vibration and noise Low cost

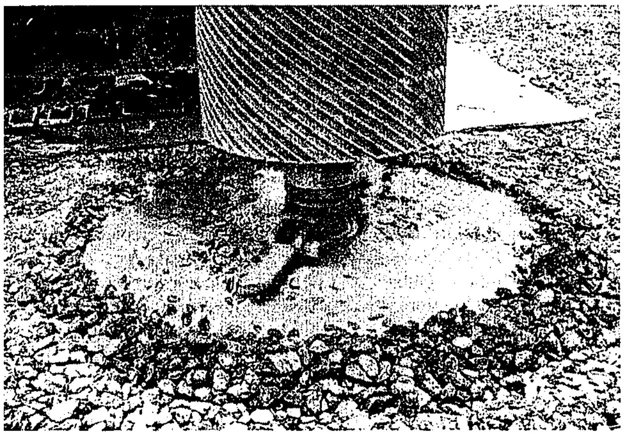


Photo 2 Start of Gantetsu pile driving

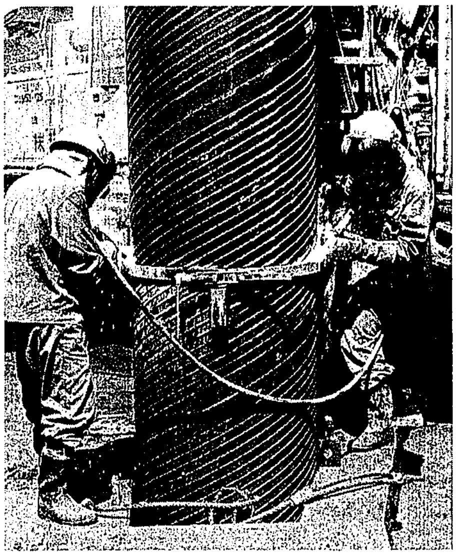


Photo 4 Site welding of steel pipe with outside surface projections

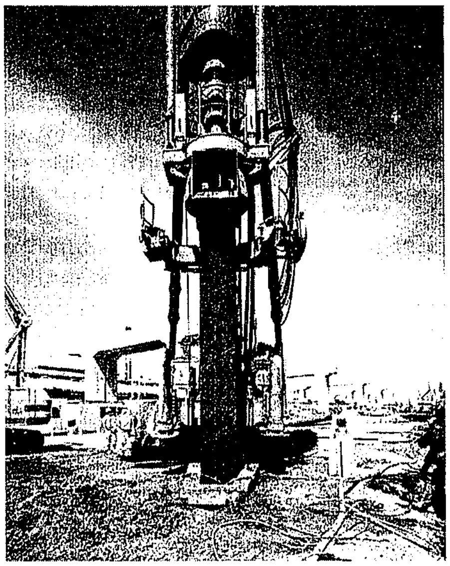


Photo 3 Installation of Gantetsu pile at construction site for New Meishin Expressway

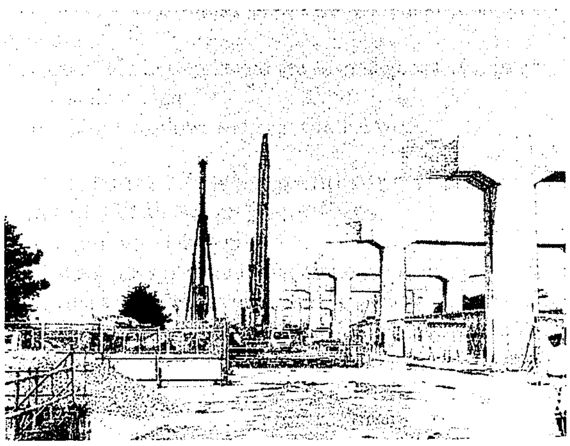


Photo 5 Installation of Gantetsu piles at construction site for New Meishin Expressway

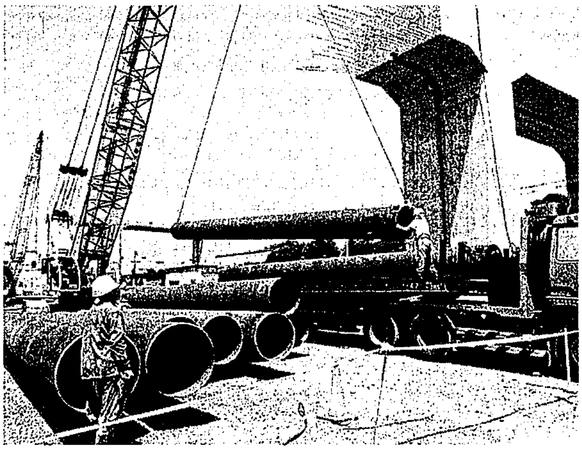


Photo 6 Transportation of steel pipes to site

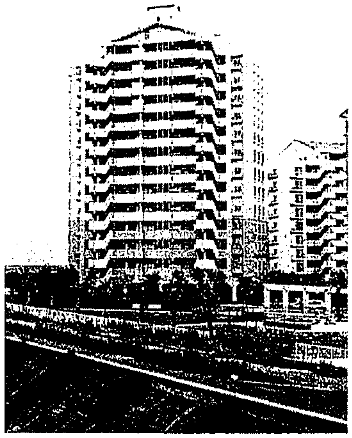


Photo 7 High-rise apartment housing constructed by using Gantetsu piles (14-story WRC)

6. Conclusions

The Gantetsu pile is a typical example of a new building construction material created by the fusion of steel manufacturing technology, design technology, and construction technology. As composite piles consisting of a steel pipe and soil cement column, the Gantetsu piles have many advantages, such as small soil discharge, low vibration and noise, large bearing capacity, and excellent seismic resistance. They have a potential for further growth. We will continue to improve and refine them.

The authors are indebted to the Housing and Urban Development Corporation, Kubota Corporation, Tenox Corporation, Japan Highway Public Corporation, and many other organizations and individuals for guidance and cooperation in the development of the Gantetsu pile method.

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