Development and Commercialization of Gantetsu Composite Foundation Pile

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
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 Pipe 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. 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 piles 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 m² of site soil can meet both assure the steel pipe pen-
eration 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/cm² 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 pile pipe.

To demonstrate this mechanism, measurements and numerical analyses by FEM and other methods were carried out. A lateral pressure measuring device, called a geocell, 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
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 \( K_p \) and the pile length/pile diameter ratio \( L_D \) for various piles of the same diameter. The \( K_p \) 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 \( K_p \) 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. 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 \( \delta_{hx} \) with respect to the design yield stress \( (\sigma_{y}, = 2,400 \text{ kgf/cm}^2) \) was obtained by load control. Fully-reversed alternate loading was performed in three cycles over the amplitude \( \delta_{\Delta x} \). The amplitude was then increased by integral multiples of \( \delta_{\Delta x} \).
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 $\delta_y$, 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.

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. 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

<table>
<thead>
<tr>
<th></th>
<th>Standard design method</th>
<th>Combined effect evaluation method (seismic performance evaluation)</th>
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<tbody>
<tr>
<td>Horizontal subgrade reaction coefficient $K_s$</td>
<td>Design pile diameter: soil cement column diameter</td>
<td>Design pile diameter: soil cement column diameter</td>
</tr>
<tr>
<td>Axial spring $K_a$</td>
<td>Combination of steel pipe and soil cement</td>
<td>Combination of steel pipe and soil cement</td>
</tr>
<tr>
<td>Bearing capacity evaluation</td>
<td>Skin friction; OD of soil cement column</td>
<td>Skin friction; OD of soil cement column</td>
</tr>
<tr>
<td></td>
<td>End bearing capacity; Cross-sectional area of soil cement column</td>
<td>End bearing capacity; Cross-sectional area of soil cement column</td>
</tr>
<tr>
<td>Axial force and bend excitation</td>
<td>For steel pipe alone</td>
<td>Combined effect of soil cement in steel pipe and steel pipe is converted to corresponding steel pipe wall thickness and added</td>
</tr>
</tbody>
</table>

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.

![Graph showing cost comparison of steel pipe-soil cement composite pile, inner-excavation steel pipe pile, and cast-in-place pile (reverse)](image)

<table>
<thead>
<tr>
<th>Pile diameter (mm)</th>
<th>800</th>
<th>1,000</th>
<th>1,200</th>
<th>800</th>
<th>1,000</th>
<th>1,200</th>
<th>1,500</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel pipe diameter (mm)</td>
<td>600</td>
<td>800</td>
<td>1,000</td>
<td>800</td>
<td>1,000</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Number of piles</td>
<td>42</td>
<td>30</td>
<td>25</td>
<td>63</td>
<td>42</td>
<td>49</td>
<td>36</td>
</tr>
<tr>
<td>Construction period (days)</td>
<td>25</td>
<td>19</td>
<td>17</td>
<td>34</td>
<td>26</td>
<td>47</td>
<td>48</td>
</tr>
</tbody>
</table>

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

Fig. 15  Example of economic study for Gantetsu piles
Table 3 Gantetsu pile application examples and reasons

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

Photo 2 Start of Gantetsu pile driving

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

Photo 4 Site welding of steel pipe with outside surface projections

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

References


