NIPPON STEEL & SUMITOMO METAL TECHNICAL REPORT No. 113 DECEMBER 2016

Technical Report

UDC 624 . 157 . 7

Challenges Up to the Present and for the Future on Installation Technologies and Design of Steel Pipe Piles

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Abstract

The use of steel pipe piles increased in Japan during the 1950s; at that time, they were driven mainly by the impact hammer (piling) method. Then, in response to the social requirement for minimum noise, vibration and waste soil, high bearing capacity and low costs, various steel pipe piling methods unique to Japan were developed and put into practice. More recently, against the background of the development of piles of high bearing capacity and increased seismic force to be considered in structural design, demands have increased for steel pipe piles and joint structures of higher strength and rigidity. Over the last few years, quick piling work at increasingly restricted sites in urban areas is being requested, renewal or reinforcing works of existing structures are being conducted often under restricted conditions such as limited overhead clearance, and an increasingly higher level of quality control is required while skilled labor decreases. Various types of steel pipe piles and piling methods have been developed to cope with these conditions and requirements. This paper gives an overview of the history of pipe pile technologies, and investigates the latest technical development trends to respond to the requirements with reference to some examples.

1. Introduction

The first steel piles in Japan were steel bars imported from the UK in 1870 for the foundation of the Kohrai-bashi Bridge in Osaka; they had helical flanges for rotation driving at the tips. Steel pilings having similar helical flanges were used for the Yamashita Oh-Sambashi Pier in Yokohama, the construction of which began in 1899.[1] After World War II, steel pipe piles were used for the pier of Shiogama Port, Miyagi, in 1954, and thereafter, the use of steel pipes for foundation pilings increased during the period of Japan's economic growth (from the mid–1950s through the 60s); they were driven by the impact hammer (piling) method at that time. Since then, the piling method and the pile design have evolved according to social requirements. New pile driving methods causing less noise and vibration appeared in the 1960s, and since then, a great number of piling technologies have been proposed and put into practice in Japan in response to increasingly diversified social needs.[2] The history of steel pipe piles is that of the development of driving methods in response to the social requirements and atmosphere that changed periodically.

The demand for pipe piles of high-strength and high-rigidity has grown over the past few years against the background of the need for higher bearing capacity, introduction of advanced design methods and larger loading considered in structure design. The space for construction work has become restricted in urban areas: structures are built at limited sites in shorter periods, they are renewed or reinforced often under small overhead clearance, and higher quality is required for the foundations, while skilled labor decreases. The technical development in the field of steel pipe piles has improved piling methods, and new steels, accessories and joint mechanisms have been devised in response to such changes in social conditions.

The present paper looks back over the historical development of the technologies of steel pipe piles, examines the latest principal requirements in the field and the trends in technical development to respond to them, and introduces some of the latest technologies.

2. History of Steel Pipe Pile Technology

2.1 Expanded use of steel pipe piles driven by impact piling

Steel pipe piles have been widely used in Japan since the mid 1950s, and their annual production was 0.8 to 1 million t (unless otherwise specified, all the units herein are metric) in the early

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1970s, larger than what it is today. At that time, piles were driven mostly by impact piling, and big buildings and structures were erected rapidly during the period of high economic growth thanks to larger piling machines of higher efficiency. Impact piling is suitable for steel pipe piles of high strength and thin walls, excellent in bearing capacity and economical because of high driving speed and no waste earth. It is also reliable because the driving end depth can be effectively defined based on the dynamic bearing force control. These advantages of the impact piling method still hold true; it is one of the best piling methods in terms of cost performance and reliability, and is still used widely for port construction, etc., where regulations on vibration and noise are more relaxed. From the 1960s, however, the concern about public nuisance increased, the noise, vibration and oil droplets from piling machines began to be regarded as problems, and after the enactment of the Noise Regulation Act in 1968 and that of the Vibration Regulation Act in 1976, the method became impracticable in urban zones.

2.2 Low-noise, low-vibration piling methods —Development of inner excavation and vibratory hammer methods

As steel pipe piles were effectively used in quantities in large unit lengths for structures on soft ground, the above restriction on the impact piling in urban areas, where soft ground is widely prevalent, constituted a serious problem, and new piling methods were eagerly sought to solve the problem.

One of the early attempts to drive pipe piles causing low noise and little vibration was the inner excavation method shown in **Photo 1**; it was further modified later into various piling methods for pipe piles. It was initially developed in the 1960s, then, other piling methods having characteristic features in the driving and foot protection processes were proposed and made widely available. The method for evaluating the bearing capacity of the steel pipe piles installed by the inner excavation method was defined in the Specifications for Highway Bridge[3] of the Japan Road Association in 1992. Jointly with Tenox Corporation, Nippon Steel & Sumitomo Metal Corporation developed the TN Method,[4] whereby the pile tip was protected by injecting cement milk into the soil at high pressure to agitate and solidify it; the method was employed for pipe piles and pipe sheet piles for foundation construction of road bridges and the like. With the inner excavation method, many of the advantages of impact piling were lost; the bearing capacity was smaller because the soil underwent no lateral pressure or stress history during pile driving without impact; waste earth arose; it was not easy to confirm if the pile tip reached the bearing stratum; etc. Nevertheless, steel pipe piles continued being used in quantities mainly for the foundations of bridges and civil engineering structures in urban areas in appreciation of their strength, rigidity and other material properties. In fact, their consumption is still high, albeit somewhat less than what it once was, supported by new driving methods introduced lately.

Another piling method is the vibratory hammer method shown in **Fig. 1**; this method does not involve earth augers or cement, but maintains the advantages of the impact piling method to some extent while reducing the noise and vibration. By this method, pipe piles are driven into soil under the load of the hammer and its vibration. It began to be used widely around 1970, and measures were taken to reduce the adverse effects on outside construction sites by variable control of the force and amplitude of the vibration and use of high-frequency waves. Its latest version uses a water jet at the pile tips to soften the soil and drive the piles more quickly. The application reference of the vibratory hammer method to bearing piles,

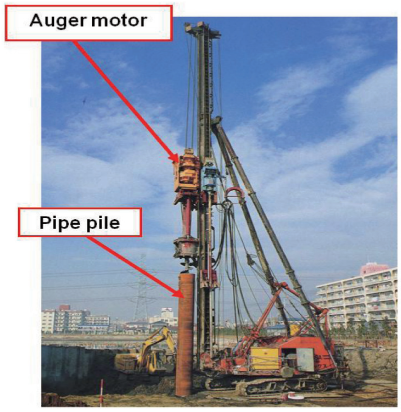


Photo 1 Inner excavation method

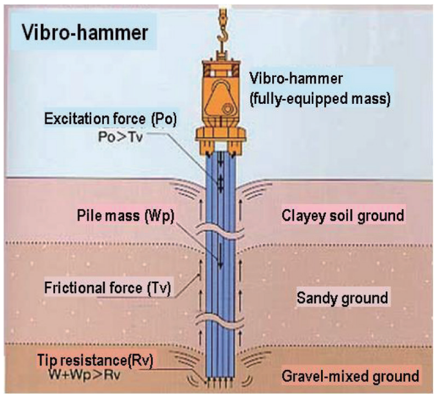


Fig. 1 Vibratory hammer method

however, was slower than those of the other methods, and the method only became widely practiced after sufficient bearing capacity data were accumulated and the bearing capacity by the method was evaluated in the Specifications for Highway Bridges[5] as late as in 2002.

2.3 Performance improvement and response to varied requirements —Technical development unique to Japan

Although the inner excavation method solved the noise and vibration problems, it brought about problems of less bearing capacity, lower piling speed, generation of waste earth and the difficulty in defining the piling end depth. The problem of vibration persisted with the vibratory hammer method, albeit considerably reduced, and the water jet, which was introduced as a measure against it, caused uncertainty about the bearing capacity. In view of this, a new stage of technical development began aiming at solving the remaining problems and enhancing the cost performance, the environmental amenity and the reliability of the driving work of pipe piles. As a result, Nippon Steel & Sumitomo Metal developed the following unique driving methods for pipe piles and offered them at the market.

2.3.1 Gantetsu Pile™, piling method of high bearing capacity and less waste earth for civil engineering structures

The Gantetsu Pile method was developed through joint development with Tenox and other partners. It is a steel pipe and soil cement piling method whereby, as seen in **Fig. 2**, the soil is excavated vertically, stirred and mixed with injected cement milk to form columns of soil cement, which are then unified with steel pipes with protru-

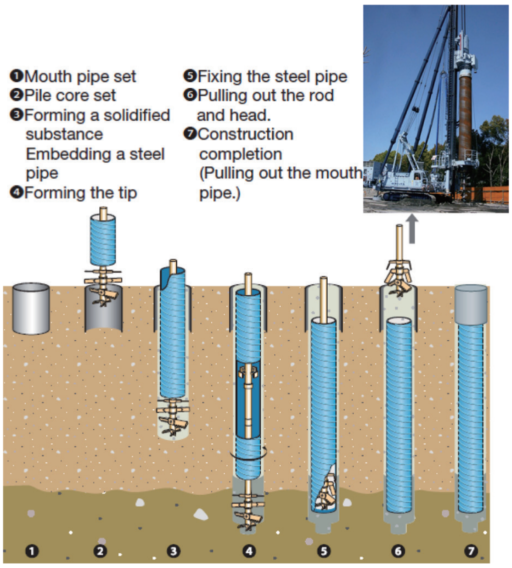


Fig. 2 Gantetsu Pile™ (steel pipe - soil cement composite pile)

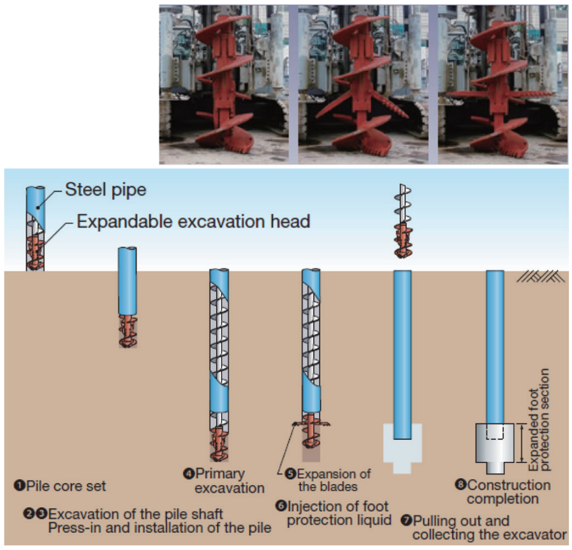


Fig. 3 TN-X™ method (expanded foot protection steel pile)

sions on the outer surface. It can form piles of high bearing capacity with low emission of noise and vibration, while part of the excavated soil is used for the soil cement to decrease waste earth discharged to outside.[6] The tip resistance and the skin friction of the piles formed by this method can be evaluated based on the diameter of the soil cement columns. The method offers good bearing capacity, and under favorable conditions, it is possible to build foundation structures more economically than with cast-in-place concrete piles.

The Gantetsu Pile was first employed for a building foundation in 1990, and thereafter, in appreciation of its tip resistance, skin friction and horizontal resistance well balanced with each other at a high level, was applied mainly to civil engineering, where the resistance to pulling force and lateral deformation often constitutes a dominant factor in foundation design; it has been employed for the foundations of more than 400 road bridges and other structures. There are cases where the bearing stratum is so deep that it is too costly to support a structure with tip bearing piles only, and the method has been effectively employed recently for an increasing number of cases to form friction piles. In addition, its application to different ground conditions is increasing such as harder soils of weathered or soft rock (of the CL class).

2.3.2 TN-X™ method —Ultra-high-bearing-capacity piling method for building foundations

The TN-X method is a method for forming expanded foot protections at the tips of steel pipe piles; it was developed jointly with Tenox. As seen in **Fig. 3**, at the end of each steel pipe pile, an expanded foot protection having a diameter up to twice that of the pile proper is formed, and thanks to the expanded excavation only at the pile tip, the tip bearing capacity is increased to nearly four times that of an inner excavation pipe pile of the same diameter,[7] which means less excavation volume per unit bearing capacity. Another advantage of the method is that piles can be installed to great depths by using inner excavation. Because of these advantages, the method has been used for a large number of distribution centers and warehouses at coastal locations, where the soil is soft and the bearing stratum is deep, while heavy loads are imposed on the building columns.

Since its first application in 2005, the TN-X method has been employed for many building foundations, where vertical bearing capacity is essential. Vertical misalignment of piles is small by the method, the position accuracy is good, and for this reason, it has been used for a great number of buildings in combination with anti-seismic pile-top isolators. Now that high pile-tip bearing capacity is obtainable by the TN-X method and the pre-boring method for forming expanded foot protections for pre-cast concrete piles, from the viewpoint of the balance between the bearing capacity and the pile strength and the need for redundancy in consideration of the uncertainties in design and construction work (which will be discussed herein later), the pursuit for greater bearing capacity seems to have reached its limit.

2.3.3 NS Eco-Pile™ —Environment-conscious, high-bearing-capacity piling method for civil engineering and buildings

The advantages of impact-driven steel pipe piles are high bearing capacity, no waste earth, easy detection of the pile tip reaching the envisaged bearing stratum, and no use of water or cement. A new, rotation-penetrated type of steel pipe pile that had the above advantages and yet caused little vibration or noise was proposed and commercially used from around 2000. Nippon Steel & Sumitomo Metal developed NS Eco-Piles shown in **Fig. 4** and **Photo 2**, obtained ministerial approval for their use for building foundations in 2000 and a technical performance evaluation certificate by an authoritative third party in 2004, and in addition, had their bearing capacity evaluated by the Railway Technical Research Institute. The diameter of the helical blade is generally 1.5 or 2.0 times that of the pipe diameter. When the helical blade has a diameter twice that of the pipe pile proper, the bearing capacity against a downward load exceeds that of an impact-driven pipe pile or a steel pipe/soil cement pile of the same diameter, and because of the blade, it exerts a high resistance to upward force. This type of pile has the following additional advantages: it is applicable to soils with artesian water or buried streams because no cement is used; piling at restricted sites is easy because of the small number of auxiliary machines; it can be driven obliquely; it can be extracted by reverse rotation; etc. In appreciation of these advantages, NS Eco-Piles have been used widely for the foundation work of buildings, roads and railway structures to solve various problems.

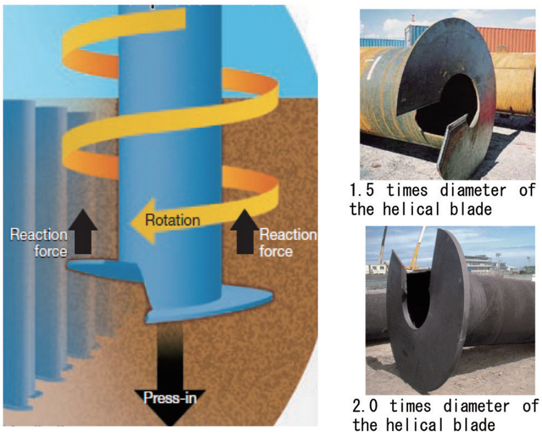
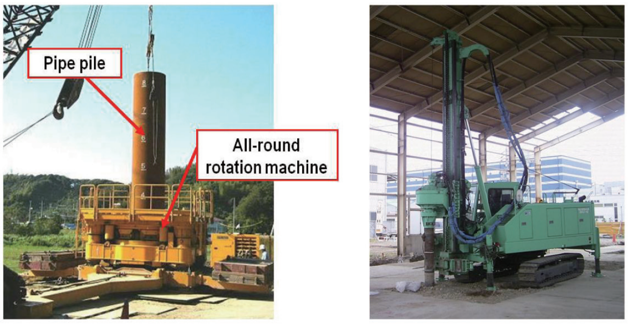


Fig. 4 NS Eco-Pile™ (rotation press-in pile)



(a) Large-diameter pile (b) Small-diameter pile

Photo 2 Example of construction using NS Eco-Pile™

2.3.4 RS Plus™ method —Low-noise, Low-vibration, High-bearing-capacity piling method for port construction

Low noise and vibration has been required more often recently even for port construction work, and the vibratory pile driving method with water jet injection is being considered more often as an applicable method. However, it was feared that the water jet would disturb the bearing stratum and adversely affect the bearing capacity, but how to estimate such adverse effects was a problem. As a solution, Nippon Steel & Sumitomo Metal developed the RS Plus method jointly with the Port and Airport Research Institute and Chowa Kogyo Co., Ltd.[8] The method, which was commercialized in 2009, consists of driving steel pipe piles, each having some ribs welded to the inner or outer surface near the lower end, with the assistance of a water jet and, after driving them to a prescribed depth, switching the injection from water to cement milk to form a bulbous foot protection to obtain a high bearing capacity. For more details of the method, see another article in the present issue.

2.3.5 Gyropress method™ —Environment-conscious, space-saving piling method for hard soils

A new space-saving piling method using a self-walking driving machine to press in sheet piles at low noise and vibration was developed, then a similar machine was developed to press in pipe piles, which became widely used around 1990 for construction projects principally in urban areas.[9] This press-in method for pipe piles has been modified and improved in a unique manner; in view of the recent increase in modifications, reinforcements and renewals of existing structures, Nippon Steel & Sumitomo Metal has jointly developed the Gyropress method together with Giken Seisakusyo Co., Ltd. The developed method is characterized by penetration into existing structures and hard ground in addition to good environmental performance and space saving.[10]

It was commercially launched onto the market in 2004, and has rapidly expanded its application references to improvement and disaster-prevention modifications of urban river revetment walls and road revetments, etc. The bearing capacity of a pile driven by the method has not been clearly defined, and for this reason, the method has been employed, like common press-in piling methods, mainly for wall structures meant to withstand lateral force. Lately, however, loading test data have been collected, and methods have been developed whereby bearing capacity is confirmed by imposing pressing loads on a pile after driving by pressing, and based on these, studies are being carried out on the application of the piles installed by this method as bearing piles.[10] It is being further improved to drive piles of larger diameters, strengthen pile penetration into harder rocks and concrete structures. The measures to expand the applicability of the Gyropress method are explained in more detail in another article of the present issue.

3. Challenges of Steel Pipe Piles and Latest Trend of Technical Development

The performance of steel pipe piles has improved remarkably through the development of various driving methods; the improvement of bearing capacity is especially significant. After the Hanshin-Awaji Earthquake in 1995 and the East Japan Earthquake in 2011, the external force taken into account in structural design and the performance required for foundation piles have increased, and the increase in the loads that a pile is supposed to withstand poses new technical problems. Other problems that require solving have arisen: many infrastructure facilities require repair or renewal, but such work has to be done under restricted conditions, and, while a higher quality level is required, shortage of labor, especially of skilled labor, is being felt increasingly strongly. All these problems are common to all piling methods. A wide variety of pile driving methods have been made available, and the market requirement is diversifying while little growth is expected of the market, and it is becoming increasingly difficult to develop a new process involving sizable investments. In this situation, the technical development in the field of steel pipe piles focuses more on the improvement of existing methods such as development of new steel materials, accessories and joint structures, measures for shorter construction periods, labor saving, enhanced work reliability, etc. than on the development of radically new processes.

3.1 Measures to increase strength and rigidity of pipe piles

After the inclusion of JIS G 3444 (Carbon steel tube for general structural purposes) in the JIS system in 1961 and that of JIS A 5525 (Steel pipe piles) in 1963, the material specifications were not changed significantly for a long period. As a result of higher bearing capacity and increased seismic load that steel pipe piles were required to withstand, however, higher resistance to axial and lateral forces than ever became a necessity for them, and it became increasingly difficult to secure sufficient strength and rigidity of piles using conventional steels and within traditional size ranges.

3.1.1 Development of high-strength steel for pipe piles

Wall thickness is increased as a measure to raise the strength of a steel pipe pile. Large-diameter pipe piles are mostly made of spirally welded pipes, made by spirally winding hot-rolled strips and welding the joints by submerged arc welding. The maximum thickness of hot-rolled strips is roughly 25 mm, and when a larger wall

Table 1 Mechanical properties of high strength spiral steel pile

(a) NSPP™ 540

Thickness t (mm)	Tensile strength (N/mm^2)	Yield stress (N/mm^2)	Yiled ratio (%)	Elogation (gauge length 50 mm) (%)	Charpy impact absorbed energy of base material (J)	Tensile strength of weld part (N/mm^2)
6	540 min	400–580	90 max	19 min	27 min at 0°C	540 min
6 < t ≤ 9				22 min		
9 < t ≤ 12				24 min		
12 < t ≤ 16				27 min		
16 < t ≤ 19				29 min		
19 < t ≤ 22				31 min		
22 < t ≤ 25				33 min		

(b) 570N/mm^2 class spiral steel pipe pile

Thickness t (mm)	Tensile strength (N/mm^2)	Yield stress (N/mm^2)	Elogation (gauge length 50 mm) (%)	Charpy impact absorbed energy of base material (J)	Tensile strength of weld part (N/mm^2)
5 < t ≤ 16	570 min	460 min	19 min	47 min at −5°C	570 min
t < 16		450 min	26 min		

thickness is required, pipes made by bending heavy plates by rolls or presses are necessary, but these pipes are more expensive and the lead time is longer. To solve the problem, spirally welded pipe piles of higher strength began to be developed; Nippon Steel & Sumitomo Metal has made pipe piles of NSPP™ 540 (standard yield point of 540 N/mm^2) and even those of a 570-N/mm^2 class commercially available in the market in addition to conventional products of SKK400 (235 N/mm^2) and SKK490 (315 N/mm^2) under JIS A 5525.

Table 1 shows the mechanical properties of these high-strength spiral pipe piles. NSPP 540 given in part (a) has been approved by the Minister of Land, Infrastructure, Transport and Tourism as pipe piles for the foundations of building structures, and the steel for the piles shown in part (b) is that for pipe piles developed based on the specifications for SM570 steel plates. The yield points of these materials are higher than that of SKK490 by 25 to 40%, effective for high bending resistance. These pile products are not included in the JIS system yet, and therefore, are subject to certain restrictions about product sizes and the method, consumables, conditions, etc. for site welding. In addition, because their rigidity is the same as that of conventional piles, and when lateral displacement is the decisive factor in the structure design, their use cannot be regarded as an effective measure. Nevertheless, their use is increasing because they are effective when the stress capacity of pipe piles is insufficient with conventional products.

3.1.2 Development of steel pipe piles with welded protrusions — Composite piles of steel pipes and concrete

Another measure to raise the strength of a steel pipe pile is combining steel pipe with concrete to form a composite pile; materials and accessories are being developed for this purpose. For composite piles, steel pipes with protrusions on the inner surface have long been available for cast-in-place piles of steel pipes and concrete. Such pipes can be produced in quantities at high productivity since the protrusions can be formed on the surface of the material steel strips during hot rolling, but when steel pipes of different wall thicknesses are required in small quantities, manufacturing efficiency may be low. In addition, the size of the protrusions, the strip thickness and the material steel grade are limited.

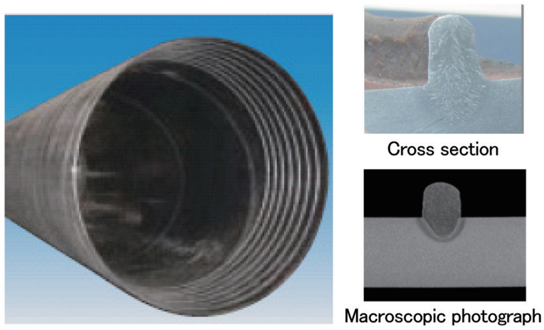


Photo 3 Steel pipe pile with welded protrusions

In consideration of the above, the company has developed a process to form continuous protrusions of desired sizes in a necessary number of rows at designated positions of the surface of manufactured steel pipes by continuously depositing weld metal, and made products with such protrusions available for different applications. **Photo 3** shows the product and sectional views of the protrusion. It is possible by this method to form protrusions on the inner surfaces of steel pipes regardless of the size, the steel grade or the production quantity. When, however, the protrusions are required in too many rows, in the entire pile length, for instance, the conventional method of forming them by rolling may be more suitable. Therefore, either of the two protrusion forming methods is selected according to the requirement and conditions.

(1) Type and purpose of protrusions

The welded protrusions are available in three different heights according to the mode of use and the type of the structure: 6, 8 and 13 mm. They can be formed either on the inner or the outer surface. Because a welding machine specially designed for the purpose is used, protrusions of uniform size and shape can be formed, although there are some limitations on the pipe diameter and the distance of the protrusion from the pipe tip. The welding method for depositing the protrusions has been appropriately established through tests using pipes of different diameters, wall thicknesses and steel grades. As shown in the sectional views of Photo 3, good penetration is obtained to adequately unify the protrusion with the base metal.

The protrusions have been proven to have sufficient strength through shear test, tensile test, etc. This is true also with the base metal pipes: through tensile tests in the axial and circumferential directions of test pieces cut out from the weld joints of the protrusions, the pipes have been confirmed to clear the required performance figures. The same tests were conducted also on pipe piles of the NSPP540 and the 570-N/mm^2 steels, and the prescribed shape, quality and strength of the protrusions were verified.

In addition to the said cast-in-place composite piles, steel pipe piles with welded protrusions are useful also for concrete-filled steel pipe piles shown in **Fig. 5**[11] and for fixing the pile tip protection as illustrated in **Fig. 6**. Various technical assessment and certification methods are available for evaluating the adhesion of the protrusions with the composite material for different applications and according to the field and conditions of application. As an example, **Fig. 7** shows the method used for railroad structures for evaluating the bonding strength between the inner protrusions and infilled concrete.[12] Here, taking the restricting effect of the steel pipe into consideration, a parameter considering the ratio t/D between the pipe wall thickness and the diameter is used together with the concrete strength f_{cu} and the ratio h/s between the height of the protrusions and the distance between them. This strength evaluation is based on data collected through tests under widely varied conditions. The welded protrusions have the same bonding strength to concrete as that of welded flat or round steel bars used as shear connectors.

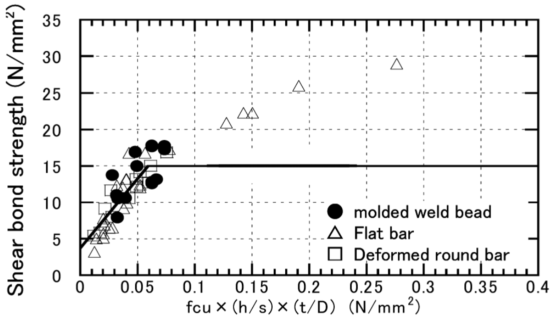


Fig. 7 Shear bond strength between steel pipe with inner ribs and infilled concrete

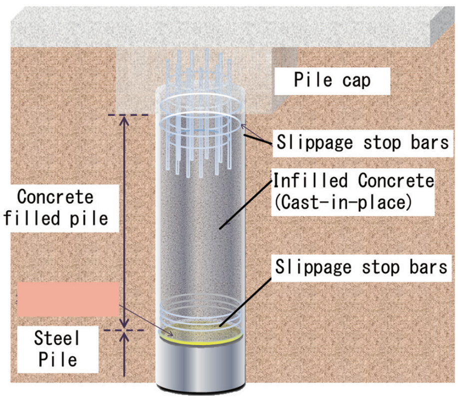


Fig. 5 Concrete filled steel pipe pile method

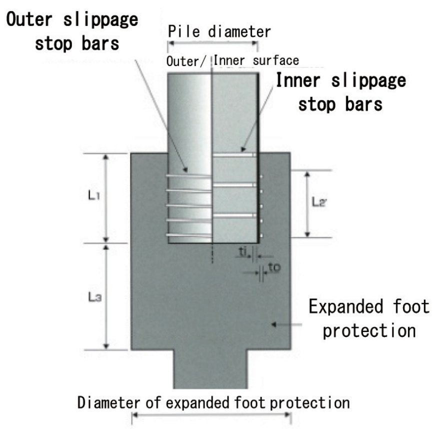


Fig. 6 Use of welded protrusions for fixing pile tip protection

(2) Hybrid pipe pile method—Concrete-filled steel pipe piles

As seen in Fig. 5, a composite pile is formed by filling the pile head portion of a steel pipe pile, where large sectional force is applied during earthquakes, with concrete. Here, shear connectors are provided near the top and bottom ends of the infilled section, and welded protrusions can be used for this purpose, too. For building foundation applications, Nippon Steel & Sumitomo Metal obtained the performance verification by the General Building Research Corporation of Japan for the foundation design in 2008,[13] and based on this, included NSPP540 in the product lineup of steel pipe piles for high-strength, concrete-filled pipe piles in 2013.[11] For civil engineering applications, design methods using these pipe piles are given in a technical performance evaluation certificate by an authoritative third party for rotation-driven pipe piles.[14]

Concrete is cast into the pile inside after its driving and cleaning dirt off its inner surface. Since the inner surface cleaning is performed often from the ground level, the length of the concrete-filled portion used to be up to 5 m in most cases, but after the development of washers to spray water and air at high pressure, it became possible to clean deeper inside the pile, forming hybrid piles having concrete-filled portions longer than 10 m.

3.1.3 Increase in pipe pile diameter

The load bearing capacity and rigidity of a pipe pile can be increased also by increasing its diameter, but larger diameter piles require larger driving machines and increase material consumption and waste earth. When pile diameter is increased to obtain greater strength against lateral force, the vertical bearing capacity often becomes excessive, which means excessive cost. Nevertheless, diameter increase is the most effective measure to improve the rigidity of piles to prevent deformation under seismic force, sometimes more economical than the increase in wall thickness, use of higher steel grades or forming composite piles. Thus it is important to select the most rational solution in the foundation design stage.

The largest possible pile diameter is different depending on the driving method and the type of application. While pile diameter is naturally limited by the capacity of existing piling machines and related facilities, the range of pile diameter is defined in design standards in consideration of past references and bearing capacity confirmed through loading tests. For instance, the Specification for Highway Bridges[15] sets forth the approved range of pile diameter usable for calculating the bearing capacity of piles driven by different methods as shown in **Table 2**. For building foundations, on the other hand, the conventionally accepted maximum pile diameter is roughly 1200 mm, allowing for some difference depending on the approved ranges for different driving methods.

On the other hand, aiming at expanding the applicability of each piling method, studies have been made to construct piles of increasingly larger diameters. In fact, steel pipe piles with a diameter of 1500 mm have been driven for railroad structures by the Gantetsu Pile method, and the RS Plus method has proved capable of driving piles up to 1600 mm in diameter,[16] while those of 1500 mm in diameter have actually been driven. As a result of the development of large piling machines for the Gyropress method, the largest pile diameter using the method has been expanded to 2500 mm. In addition, the largest pile diameter for the TN-X method has been increased from 1 200 to 1 400 mm,[17] while that of the NS Eco-Pile to 1 600 mm,[18] which has been accredited by an authoritative third party.

3.1.4 Revival of batter piles

In addition to the increase in load bearing capacity of pile, foundation structure employing batter piles is attracting attention as another measure to resist seismic force. Since batter piles convert part of the horizontal force to axial force and transmit it to the bearing stratum, a foundation structure with them has a large resistance to horizontal force. For this reason, batter piles are effective at suppressing horizontal deformation in soft soils or for compact foundation design at restricted sites. Since the basic design philosophy for the foundation structure using batter piles was described in the Pile Foundation Section of the 1964 version of the Road Bridge Substructure Design Guidelines,[19] the predecessor of the Specifications for Highway Bridges, this was a common practice up to the 1970s. Their use for bridges in land areas, however, has become virtually non-existent recently for reasons such as (i) the impact piling method capable of driving batter piles was practically banned in land areas, (ii) no methods were established for evaluating the effect of consolidation settlement of soft and viscous soil, for which batter piles were assumed to be used effectively, on the piles, and (iii) no methods for evaluating the load bearing capacity and the deformability of batter piles were given for foundation design in consideration of large seismic force, which became emphasized after the Hanshin-Awaji Earthquake in 1995.[20]

Of the above problems, (i) was solved as the rotation-piles became widely used. Then both (ii) and (iii) were also solved as a result of energetic researches and studies of the Public Works Research Institute and the Japanese Association for Steel Pipe Piles: regarding (iii), the resisting mechanism of a batter pile to large seismic force was clarified and its allowable ductility factor proposed based on the results of loading tests using combined piles,[21] and regarding (ii), which remained as an outstanding problem, the deformation mechanism of a batter pile under consolidation settlement was clarified, and a practical method was proposed[20] for evaluating bending moment as shown in **Fig. 8**.[15] Based on all of these, explanations on the design philosophy for batter piles reappeared in the 2012 revised version of the Specifications for Highway Bridges.[15] As a result, the number of foundations using batter piles is increasing gradually.

Table 2 Application range of conventional bearing capacity formula in specification for highway bridges

Pile installation method	Application range of conventional bearing capacity formula	Bearing layer
Impact hammer Vibratory hammer	Approximately up to 1 500 mm in pipe diameter	Sand, gravel, clay
Inner excavation (type of soil cement foot protection)	Approximately 500–1 000 mm in pipe diameter	Sand, gravel
Steel pile - soil cement composite	Approximately 800–1 300 mm in pipe diameter	Sand, gravel
Rotation press-in pile (screwed pile)	Approximately 400–1 200 mm in pipe diameter	Sand, gravel

3.2 Measures for quick site welding, labor saving and quality ensuring

As the use of pipe piles of larger diameter, thicker wall and higher strength expanded, and piling work under severe conditions increased, for example, under existing bridge girders, adjacent to busy railway lines, etc. often seen with renewal or reinforcing works of infrastructures, problems related to site welding became tangible. Welding naturally takes longer as the diameter and the wall thick-

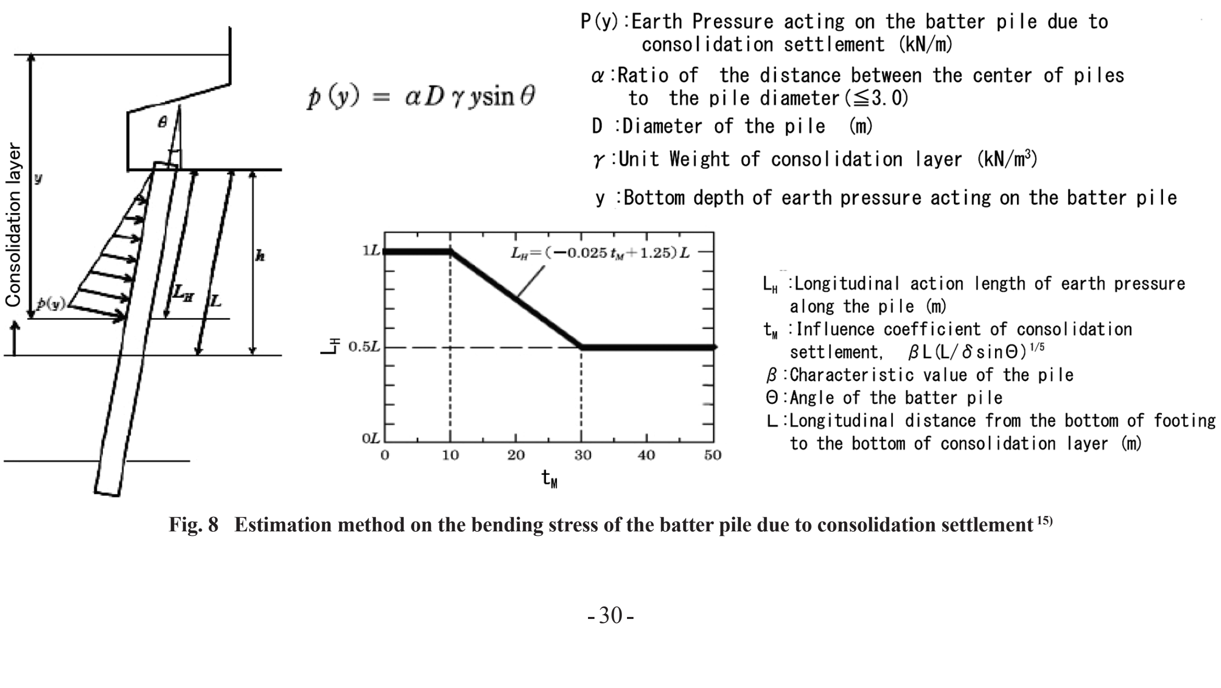


Fig. 8 Estimation method on the bending stress of the batter pile due to consolidation settlement[15]

ness of the pipe piles increase, and when overhead clearance is limited and short piles have to be welded one to another, the total piling time is often determined rather by welding time than driving speed. In the cases of piles of high-strength steel, the strict requirements related to welding conditions and consumables may make it worse. The recent shortage in skilled labor adds yet another problem. All these make it difficult to secure the quality of pile joints welded on site under different conditions. In consideration of the increasingly higher quality required for the joints, the need for stricter and more frequent inspection is increasing, and as a result, so are the problems and the load of site welding of pile joints.

In this situation, interest is increasing in mechanical joints, which enable quick joining of piles regardless of the diameter and wall thickness.[22] One such example is the Laqnican™ Joint shown in **Fig. 9**; the demand for it has increased rapidly over the past few years. The advantages of mechanical joints are short time, stable joint performance unaffected by the skill of labor, weather or other site conditions, but they are expensive since their components are manufactured using high-quality materials and precision machine tools. To solve the problem, Nippon Steel & Sumitomo Metal is developing new types of mechanical joints with improved structures. One of such mechanical joints is reported in another article of the present issue.

In addition to the development of mechanical joints, studies have started to develop methods for automatic site welding of pipe pile joints. While such studies focus on securing good welding quality and relaxing restrictions on welding positions and workers' loads rather than shortening the welding time, some new methods have been put into actual practice.[23, 24] While some manual work remains at present for preparations, welding process control and adjustment of the machines, further improvements are being pursued for thorough automatization and labor saving.

3.3 Strengthening and quality ensuring of pile-head connection

In addition to the piles proper, adequate strength must be ensured for pile-head connections to the footings or foundation beams of the superstructure. A pile-head connecting structure widely employed for steel pipe piles used to be the one in which cages of reinforcing bars are placed inside pile heads and concrete is cast into them to connect the pile heads to the footing concrete. Later, as the use of high- load bearing capacity pipe piles increased, flare welding of anchoring steel bars vertically around the periphery of pile heads was added to the above cage method, and this anchor bar method became increasingly popular. Because of the precarious quality of outdoor flare welding, however, a movement was started to restrict this practice; in fact, the latest version of the Specifications for Highway Bridges bans the welding of reinforcing bars to pile heads.[15]

3.3.1 Revision of strength evaluation of pile-head connection with bar cages

While the Specifications for Highway Bridges bans the method of welded anchor bars, it promotes rationalization of the design of the connection: the sectional diameter of the hypothetical reinforced concrete (RC) section assumed there to be inside a footing is reviewed, and the use of high-strength SD390, SD490 or similar is allowed on condition that the bars are combined with concrete having a design strength of 30 N/mm^2.[15] Based on the results of the studies by the Public Works Research Institute and the Japanese Association for Steel Pipe Piles, the sectional diameter of the hypothetical RC section has been changed from the conventional D + 200 mm (D being the pipe pile diameter) to that shown in **Fig. 10**, and as a result, it is now possible to assume it to be larger than before when D ≥ 400 mm.[15, 25] While the conventional rule to add 200 mm uniformly to the pile diameter was established based on the results of tests using pipe piles around 400 mm in diameter, the new calculation is defined as a function of D in consideration of more recent test results and analyses using piles of larger diameters.

3.3.2 New pile-head connecting method of improved strength and deformation performance

Nippon Steel & Sumitomo Metal has developed and commercialized the enlarged outer tube method for pile head connection shown in **Fig. 11**[26] and **Photo 4**[26] jointly with Shimizu Corporation, a leading construction contractor. This method has received a build-

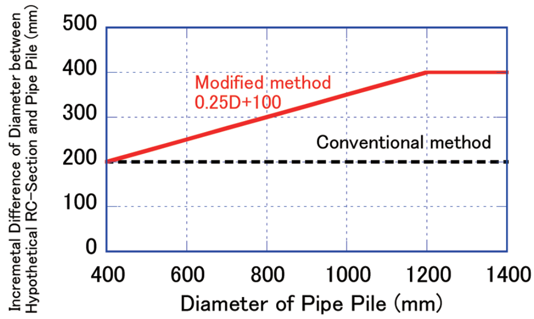


Fig. 10 Diameter of hypothetical RC-section in design of pile head connection

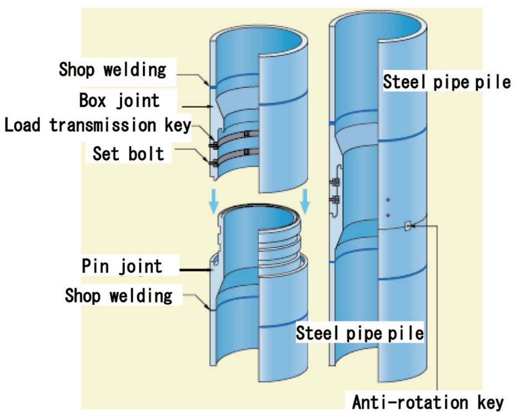


Fig. 9 Laqnican™ Joint

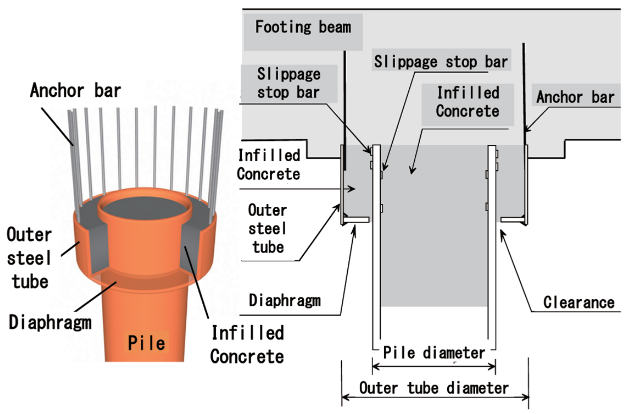


Fig. 11 Pile head connection using enlarged outer steel tube[26]

Photo 4 Setting of enlarged outer steel tube [26]

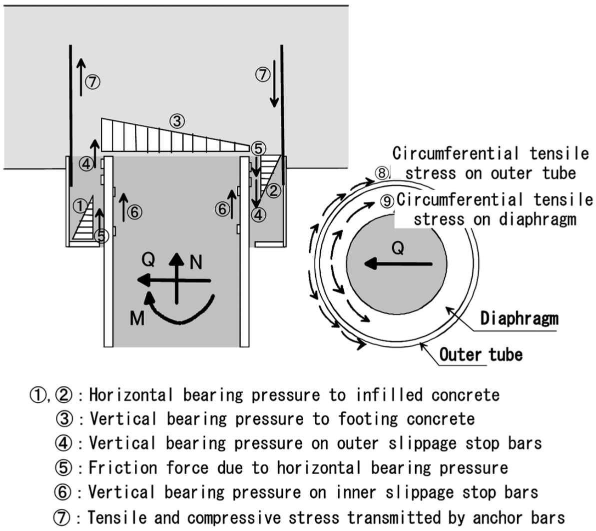


Fig. 12 Stress transfer mechanism of pile head connection [26]

ing structure performance certificate [27] from the General Building Research Corporation of Japan, and counts application references of roughly 30 foundation structures, mainly for buildings. A shop-fabricated enlarged outer steel tube, having a diameter of about 1.35 to 1.50 times the pile diameter and a length about a half of it, with a diaphragm and anchor bars, is fitted to the head of each pipe pile, and is bonded to the pile by filled-in concrete. Since the load is transferred to the base concrete via the outer tube of an enlarged diameter, large connecting is obtained with less use of reinforcing bars. Because no site welding is involved, it takes a shorter time, offers more reliable quality, and there is little restriction depending on the piling method.

Figure 12 shows the stress transfer mechanism by this pile-head connecting method.[26] The axial force, the shear force and the bending moment applied to the pile head are partially transferred to the base concrete directly contacting the pile head, and the balance to the pile-head tube via filled-in concrete, and then to the base concrete via the anchor bars. From the results of various tests and analysis on the strength and deformation performance of pile-head connections,[26, 27] this connecting structure was confirmed to exert excellent and stable bearing capacity thanks to the following mechanisms: exercising the circumferential tensile strength of the tube wall and the diaphragm, the outer tube resists horizontal force transferred from the pile proper via the filled-in concrete; the diaphragm restricts local deformation of the outer tube wall; and the filled-in concrete is confined by the outer tube wall and the diaphragm.

The load bearing capacity of a pile head connection is determined by that of (a) the enlarged pile head composed of the outer tube, the diaphragm and the filled-in concrete, (b) the portion of the pile proper restricted by the filled-in concrete or (c) the anchor-bar connection to the base concrete, whichever is the lowest. For this reason, the strength of these portions has to be estimated at the design stage and confirmed to be sufficient for withstanding expected loads. It is possible to prevent the pile head connection from failing by designing the strength of these portions ((a)–(c)) properly such that the assumed of failure in design take place. For more details of the connection design, see the reference literature 26. While the degree of fixing and rotational rigidity of this type of pile head connection change is dependent on the axial force, as in conventional pile head connecting structures, the degree of fixing at the yield of pile head connection is presumed to be 0.7 to 0.9 from test results, roughly the same as that of the conventional rigid connection method using anchor bars.[26]

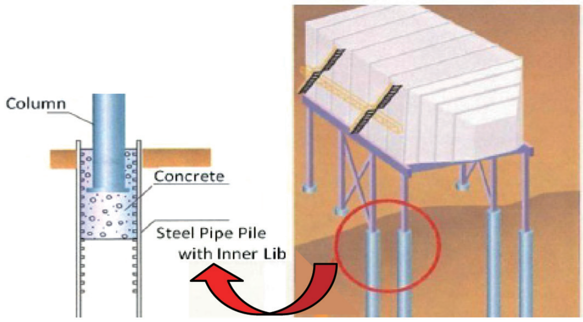


Fig. 13 Sat-in pile foundation

3.3.3 Other special pile-head connecting methods

While the performance required for conventional rigid pile head connecting structure and how to obtain it in design are clearly defined, a large bending moment is likely to be applied near the pile head, which calls for larger diameter and thicker walls of pipe piles. Thanks to the advance in structural analysis handling the super- and substructures as one unit, the cases are increasing where semi-rigid connection or seismic isolation is used at pile heads to mitigate the concentration of bending moment or shear stress near pile heads. Reducing the section force on pile heads is effective at decreasing the stress transferred to piles as well as to footing beams and the superstructure, and therefore, it is possible to rationalize the design of the super- and substructures as a whole. Since pile-head seismic isolation does not use seismic isolators between the upper and lower slabs, it is advantageous in terms of structural rationality and space saving. Many types of semi-rigid or seismic isolating pile head structures have been proposed and applied to real structures.

In addition to these, a one-pile-to-one-column structure has been developed wherein the column roots are embedded in corresponding piles. The sat-in pile foundation[28] shown in **Fig. 13** envisages reducing the number of piles by increasing the pile diameter and saving costs and labor by omitting footing beams or column fixing structures; this structure has been approved by the Building Center of Japan, and used for roughly 20 construction projects in and outside Japan, mainly for plant foundations.

4. Closing

This paper summarized the development history of steel pipe piles, and introduced new technologies in the field responding to the latest technical requirements. Owing to limited space, it was impossible to mention aspects such as anti-corrosion and endurance measures to reduce lifecycle costs and extend service life. While some requirements have been effectively met employing new technologies and design methods, many are yet to be solved and are waiting for technical solutions, and new needs will arise and require addressing as the social environment changes. Here, problems yet to be addressed and what is expected of future technical development were discussed at the close of the present article.

The needs for maintaining a high quality and technical level, measures to cope with the shortage of skilled labor and enable quick construction work at restricted sites for renewals and reinforcing works will continue to grow, and while little growth is expected of Japan's construction market, the type of work to make the most of the advantages of steel will increase. To help solve the problems of construction work at restricted sites, devising technologies for easy and safe use of steel pipe piles is essential. The current trend toward reliability-based design seems to offer a good opportunity to reevaluate the quality and the operational characteristics of other steel materials. For example, since it is possible with rotation- pipe piles to measure the change in the torque into different soil types in real time, once a technology is established to confirm the pile end hits the envisaged bearing stratum and converts driving data directly into the bearing capacity of the pile being driven, as in the case of impact driving, a more reliable pile driving method will be obtained. Thus it is necessary to pursue total performance of foundation structures in consideration of the reliability and the added value of the steel material and work method, and take actions in the reliability-based design to quantitatively evaluate pile performance.

On the other hand, pile driving into hard soils is required more often for road construction, coastal disaster protection work, etc., but adequate methods are not given for pile driving and defining bearing capacity, and as a consequence, steel pipe piles are not used widely for such work. New work methods expand the applicability of pipe piles, and, given adequate support such as methods for estimating bearing capacity, their application will greatly expand. Finally, although the development of new pile driving methods is becoming increasingly difficult, an innovative breakthrough is expected to shake up the conventional stereotype of steel pipe piles: highly reliable but expensive.

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