Technical Report

Approach of Steel Pipe Pile for Building Foundation to Adjust to Large Earthquake Design

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Abstract

In the building foundations field, various needs have arisen since the birth of steel pipe piles, including environmental considerations such as vibration and noise, higher bearing capacity, and safety assurance during earthquakes. In recent years, the experience of major earthquakes has given momentum to the introduction of design for large earthquakes (so-called "secondary design") for foundation piles. In response to the emergence of this major change in design, Nippon Steel Corporation is working to clarify the actual performance of steel pipe piles, develop a design foundation that utilizes this performance, and develop a line of products that can withstand large horizontal forces. In this paper, we look back on the historical evolution of steel pipe pile technology and introduce some of our representative products that can be combined in various ways to respond to major earthquakes and other complex needs.

1. Introduction

In the building foundation field, steel pipe pile percussion methods were employed during the high economic growth period. Thereafter, the development of the high-bearing capacity inner-excavation method, no waste earth rotating pile method, and other pile installation methods advanced in response to environmental problems such as noise and vibration in urban areas. In recent years, the experience of large earthquakes has given impetus to the discussion of the necessity of design to combat large earthquakes (so-called secondary design). Nippon Steel Corporation has clarified the performance of steel pipe piles in the event of a large earthquake, especially their deformation capacity, has worked to establish design methods that utilize this performance, and has developed comprehensive technologies by considering the secondary design.

In this paper, we review typical societal needs from the birth of steel pipe piles to the present and technological changes in steel pipe piles that meet these needs. We introduce steel pipe pile initiatives such as high strength and deformation capacity to design against large earthquakes and Nippon Steel's products that can provide resistance to large earthquakes.

2. History of Steel Pipe Piles and Development of Steel Pipe Pile Methods in Building Field

Since ancient times, wooden piles had been used as pile foundations to support buildings. From the end of the Meiji Period, as the number of reinforced concrete buildings was increased, cast-in-place concrete piles were then introduced. To support large buildings constructed on soft ground in urban and coastal areas during the high economic growth period after World War 2, the percussion method of the steel pipe pile rapidly spread thanks to advantages such as material reliability, availability, and construction speed. On the other hand, the promulgation of the Noise Control Act and the Vibration Control Act in 1968 and 1976, respectively, reduced the demand for the percussion method in urban areas. Since the 1980s, the development and adoption of the inner-excavation steel pipe pile method and the soil-cement hybrid pile method with low noise and vibration have rapidly progressed.

As buildings increased in size and height, pile foundations with greater bearing capacity have been demanded. In 2001, the Ministry of Land, Infrastructure, Transport and Tourism announced Notification No. 1113. This notification made it possible to specify the bearing capacity of newly developed pile methods in addition to general pile foundations. Consequently, steel pipe piles with their ends en-

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larged to provide a higher bearing capacity were developed. Also developed was a rotating pile method whereby a steel pipe with a helical blade at the end is rotated and driven into the ground in an environmentally friendly manner. These new piling methods allowed for economical and environmentally friendly design and construction.

3. Changes in Design in Building Field

3.1 Changes in seismic standards and guidelines and need for design to combat large earthquakes

The Building Standards Act was revised in 1981. It was stipulated that buildings must be earthquake-resistant to prevent them from being damaged in a moderate earthquake with a seismic intensity of about 5 and collapsing in a large earthquake with a seismic intensity of 6 or 7. The seismic standards under this revision came to be called the "new seismic standards" and the seismic standards before that were called the "old seismic standards". As for pile foundations, only vertical forces had to be considered previously, but horizontal forces had to be considered as well. However, the revised act presented seismic design methods of pile foundations only for earthquakes with a seismic intensity of about 5. The 1995 Hyogo-ken Nanbu Earthquake caused enormous damage to structures and human lives. Design methods of pile foundations to combat large earthquakes were shelved, however, because collapsed buildings were constructed before the introduction of the new seismic standards and because pile foundations designed according to the new seismic standards were not seriously damaged.

In the 2011 Pacific Coast of Tohoku Earthquake and the 2016 Kumamoto Earthquake, there were observed cases where the collapse of pile foundations that had not been seismically designed to combat large earthquakes tilted the buildings above and rendered them unusable. Such disaster also affected public buildings that had to continue being used after an earthquake. This situation sparked discussions about the necessity of designing foundations to combat large earthquakes.

In 2017, the Ministry of Land, Infrastructure, Transport and Tourism issued the "Guidelines for Continuity of Functions of Buildings to Serve as Disaster Control Bases."[1] The guidelines state that the foundations of buildings to serve as disaster control bases, such as government office buildings, disaster shelters, and hospitals, shall be designed to combat large earthquakes. In 2019, the Architectural Institute of Japan revised its "Recommendations for Design of Building Foundations"[2] and specified that design to combat large earthquakes (so-called secondary design) should be employed for building foundations in principle.

3.2 Improving an environment regarding design to combat large earthquakes (secondary design) by use of deformation capacity of steel pipe piles

Steel pipe piles are superior in post-plastic deformation capacity (toughness) and energy absorption performance. More rational design can be made by clarifying, understanding, and utilizing the properties of steel pipe piles. As a member of the Japanese Technical Association for Steel Pipe Piles and Sheet Piles, Nippon Steel conducted experiments and numerical analyses toward the development of the design basics, specified the deformation capacity (toughness) of steel pipe piles that had not been utilized in the building foundation field, and reflected the results in the books titled "Recommendations for Design of Building Foundations"[2] and "Strength and Deformation Capacity of Foundation Structural Members"[3] published by the Architectural Institute of Japan. In addition, we clarified the performance of concrete-filled steel pipe piles in an earthquake and published technical manuals for design methods that make use of the deformation capacity (toughness) of steel pipe piles and concrete-filled steel pipe piles. We also quantitatively evaluated the advantages of utilizing the deformation capacity of these piles.[4] These results were achieved through collaboration with the Japan Iron and Steel Federation and the Japan Society of Steel Construction.

4. Introduction of Steel Pipe Pile Methods Capable of Providing Resistance to Large Earthquakes

4.1 Introduction of steel pipe pile methods for building foundations

Nippon Steel has the TN-X method for the high load-bearing capacity piles and the NS ECO-PILE™ method for screwed piles described in Section 2. These two pile methods are introduced below.

4.1.1 TN-X method

The TN-X method is illustrated in **Fig. 1**. The pile shaft is a steel pipe. The pile has an expanded foot that has a diameter of 1.25 to 2 times that of the pile diameter and that is formed of soil cement. As shown in **Photo 1**, the expanded foot provides a high load-bearing capacity of up to 17 900 kN per pile under constant axial force.

The TN-X method allows for economic design by the reduction of the required number of piles because the load-bearing capacity is higher than that obtainable with the other piling methods. It also has the advantage of pile installation to a great depth of up to 70 m. In the initial stage of its development, the TN-X method was adopted for large-scale warehouses, hotels, and many other buildings constructed on soft grounds in the Tokyo Bay area. In recent years, the TN-X method has been adopted for an increasing number of buildings whose pile foundations must be designed to combat large earthquakes (secondary design) by taking advantage of the bending performance of steel pipe piles.

4.1.2 NS ECO-PILE™

The NS ECO-PILE™ method uses steel piles having a spiral blade at pile ends as shown in **Photo 2**. The diameter of the spiral blade is 1.25 to 2.5 times that of the steel pipe. As shown in **Fig. 2**, the steel pile is pressed into the ground while rotating the large blade. Low noise, low vibration, and no soil removal are the features of the NS ECO-PILE™ method. The spiral blade produces a large

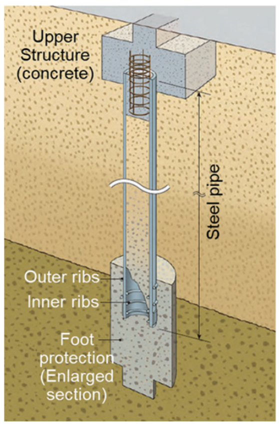

Fig. 1 TN-X method[5]

Photo 1 Expanded foot protection section[5]

Photo 2 NS ECO-PILE™[6]

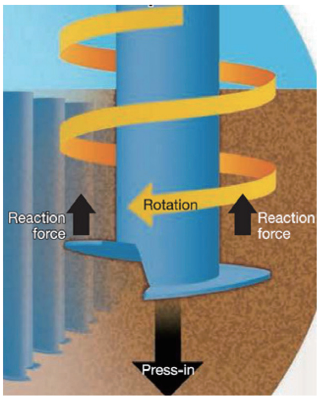

Fig. 2 Rotation press-in pile[7]

Photo 3 Small pile rotary machine[6]

Photo 4 Pile rotary machine[6]

vertical load-bearing capacity. When the pulling force is applied to the pile, the pile can withstand the pulling force due to the anchoring effect of the spiral blade. The piles are available in the diameter range of 101.6 mm to 1 600 mm.

Small-diameter piles can be installed with a small machine as shown in **Photo 3**. The NS ECO-PILE™ method is suitable for areas where the space is limited, the headspace is restricted, and the land use is limited. Large-diameter piles are installed by a body-rotating method as shown in **Photo 4**. Since cement milk is not used at all on the site, a cement plant is not required and space-saving pile installation is thus possible. Without the fear of cement milk spill, NS ECO-PILE™ is often adopted as an environmentally friendly piling method in groundwater use regions, famous water regions, sake brewing regions, and urban regions.

4.2 Introduction of peripheral technologies for adding horizontal resistance force

As peripheral technologies whereby piles can withstand the horizontal forces that increase during a large earthquake, we have a product lineup of high-strength steel pipe piles NSPP™540, the concrete-filled steel pipe pile method, and the enlarged outer tube method™. In recent years, we have advanced these technologies further. These peripheral technologies can be applied together. When combined with the TN-X method and NS ECO-PILE™ method introduced in Section 4.1, they can accommodate still greater seismic forces and meet multiple needs in addition to the load-bearing capacity requirement.

4.2.1 High-strength steel pipe piles NSPP™540

Steel pipe piles used for pile foundations are mainly STK400 and STK490 specified in JIS G 3444 and SKK400 and SKK490 specified in JIS A 5525. SKK is primarily used for high-strength

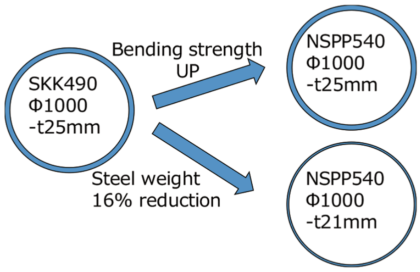

Fig. 3 Effect of using NSPP™540

pipe piles with a diameter of 600 mm or more and is manufactured and marketed by Nippon Steel. The nominal strength is specified for these steel pipe piles in the Ministry of Construction Notification #1458 of 2000. It is 235 N/mm^2 for SKK400 and 325 N/mm^2 for SKK490.

In addition to the above materials, Nippon Steel has developed high-strength steel pipe piles NSPP™540 and has acquired a minister's certification at a nominal strength (F value) of 400 N/mm^2. This provides for economic design with steel pipes of smaller diameter and wall thickness (**Fig. 3**). Self-shielded welding wires are available for NSPP™540. This means that NSPP™540 can be welded in the same way as existing SKK400 and SKK490.

4.2.2 Concrete-filled steel pipe pile method

(1) Concrete-filled steel pipe pile method

The concrete-filled steel pipe pile method fills the upper part of an installed steel pipe pile with concrete to build the pile as a concrete-filled steel pipe. Slippage stop bars are installed on the inside of the steel pipe in the section where the steel pile is filled with concrete to integrate the steel pipe with the concrete. This method provides a bending capacity high enough to withstand greater seismic forces (**Fig. 4**) and received a performance certificate from the General Building Research Corporation of Japan (GBRC). From the relationship between the applied axial force and the bending moment shown in **Fig. 5**, it can be seen that the bending capacity of concrete-filled steel pipe piles with a diameter of 1 200 mm and a wall thickness of 16 mm is almost the same as that of a wall thickness of 25 mm (in the compression region with an axial force ratio of about 15%). In 2013, the method acquired a performance certificate by adding the high-strength steel pipe piles NSPP™540 from the GBRC. This combination afforded resistance to still higher seismic forces.

The concrete-filled steel pipe pile method is characteristic in that Nippon Steel's original technique "molded weld bead" (shown in the upper right of Fig. 4) can be used as a slippage stop measure. The molded weld beads are formed by melting welding wire onto the inner surface of the steel pipe. Unlike conventional welded steel bars, the molded weld beads are integrated with the steel pipe to provide high reliability.

(2) Development of cleaning machine

When steel pipe piles are installed by the concrete-filled steel pipe pile method, the inside of the steel pipe pile must be cleaned as shown in **Fig. 6**, so that it can be properly filled with concrete. In 2014, jointly with TENOX Co., Ltd., we developed and patented a steel pipe pile inside a cleaning machine as shown in **Photo 5**. The machine ensures that the inside of the steel pipe pile is cleaned so that the concrete-filled steel pipe pile can provide the required bend-

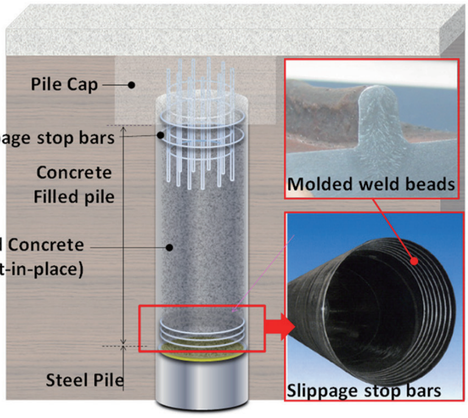

Fig. 4 Concrete filled steel pipe pile method[8)]

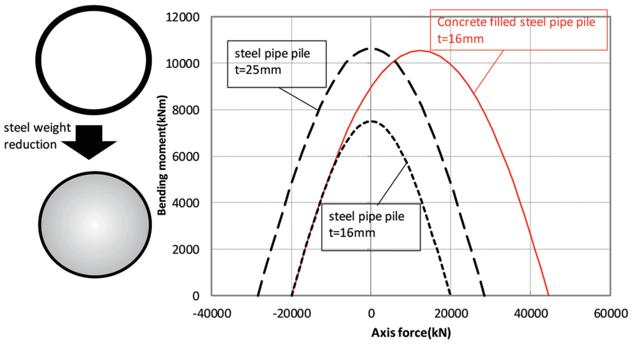

Fig. 5 Improvement of bending capacity using concrete filled steel pipe pile

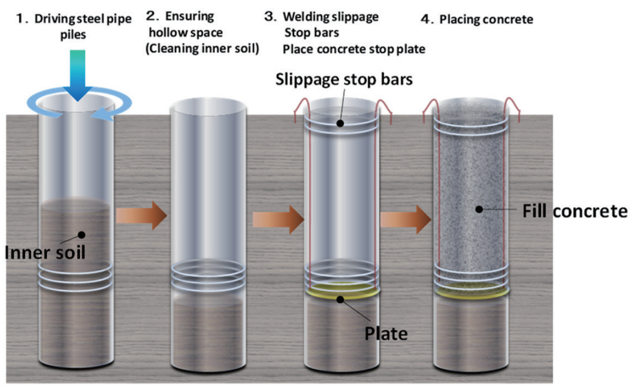

Fig. 6 Construction procedure of filling concrete[8)]

ing capacity as the composite structure. As shown in **Fig. 7**, the machine is characteristic in that it has a scraper to remove soil and sand from the inside of the steel pipe pile and a device to wash away the removed soil and sand with pressurized water and air. As shown in **Photo 6**, tests confirmed that the machine can completely remove the deposits from the inside of the steel pipe pile.

4.2.3 Enlarged outer steel tube method™

(1) Enlarged outer steel tube method™

We developed the enlarged outer steel tube method™ for pile head connection together with Shimizu Corporation. The pile head joint where the pile and the pile cap are connected is strengthened with less use of reinforcing bars, to ensure weld quality by eliminat-

Photo 5 Cleaning machine

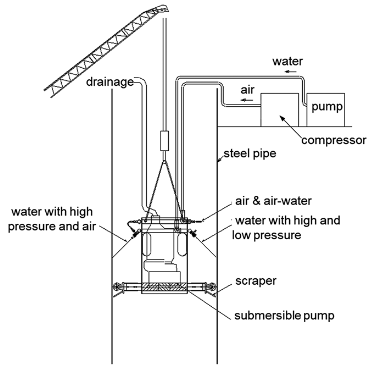

Fig. 7 Cleaning machine

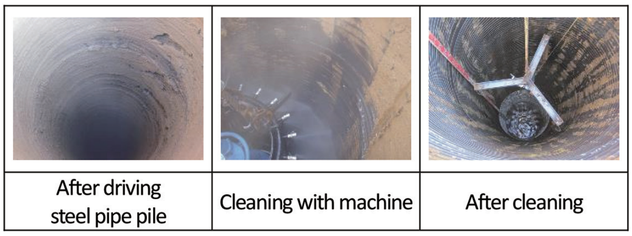

Photo 6 Before and after cleaning inside steel pipe pile

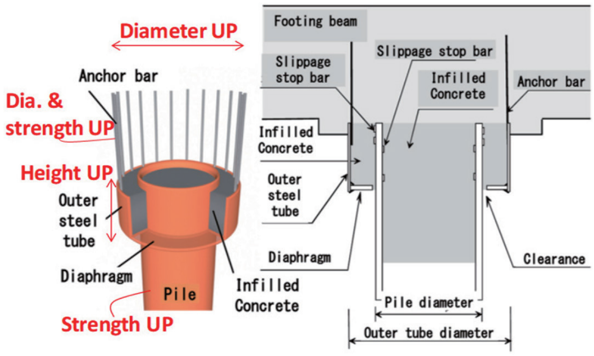

Fig. 8 Pile head connection using enlarged outer steel tube[9)]

ing on-site welding, and to shorten the on-site pile head joining period. This method can be applied not only to steel pipe piles but also to soil-cement piles and cast-in-place steel pipe piles. As shown in **Fig. 8**, an enlarged outer steel tube with a diameter 1.35 to 1.75 times the pile diameter is fabricated at a factory, is placed on the top of the pile to double tube structure, and the enlarged outer steel tube is filled with concrete to integrate the connection.

(2) New development of enlarged outer steel tube method™ to improve the strength and deformation performance

To meet the requirements of design (secondary design) to combat large earthquakes that have been increasing in recent years, we improved the strength of the enlarged outer steel tube method by about 1.5 times higher than that of the conventional type. In the development concept, we specified that the piles with higher bearing capacity should be capable of resisting the seismic load expected to occur in a large earthquake. As shown by the red letters in Fig. 8, the resistance capacity of the pile head was increased by increasing the strength of the materials of the pile and reinforcing bars as well as the diameter and height of the outer steel tube. With this double pipe structure, the movement of the steel pipe pile is constrained by the surrounding concrete. The compressive pressure of the concrete is transferred to the outer steel tube. The hoop tension is generated in the outer steel tube to develop the resistance capacity. We conducted large-scale tests and numerical analyses to investigate whether the complicated load transfer from the concrete to the outer steel tube would be properly achieved when the larger outer steel tube was used and confirmed that the expected resistance strength was achieved. In February 2021, we acquired a building structure performance certificate from the General Building Research Corporation of Japan. In October 2021, we applied the newly developed method of the outer steel tube with a diameter of 2.1 m for the first time at the construction site of a research facility (**Photo 7**). We have realized that the resistance capacity was high enough to combat large earthquakes (**Fig. 9**) and demonstrated that the newly developed outer steel tube can be installed in about 10 min per unit and can contribute to shortening the construction period.

5. Closing

In the building foundation field, we have developed and expanded our piling methods by taking advantage of steel pipe piles such as constructability and the low noise and vibration to the surrounding environment. In addition, we have clarified and defined the ultimate performance for strength and deformation which is one of the essential features of steel. Taking advantage of this feature, we have proposed design methods and have developed peripheral technologies for increasing the resistance capacity of pipe foundations to combat large earthquakes that have been increasing in recent years. We think that we can solve complex needs, such as labor-saving construction, economic design, and safety assurance in an earthquake, by combining products such as construction methods, material properties, design methods, and structures that we have constantly developed to meet the needs. On the other hand, carbon neutrality initiatives are gaining momentum to achieve a sustainable society in the world. We believe that the carbon dioxide reduction effect of the recyclability of steel materials, rational design, and shortening construction times through the use of steel materials can become new advantages of steel. Nippon Steel will continue to play a role in building a sustainable society both in Japan and overseas by providing products and services that take advantage of the features of steel while considering the life cycle of steel structures, such as maintenance and management, renewal, and reuse.

Photo 7 Setting of enlarged outer steel tube

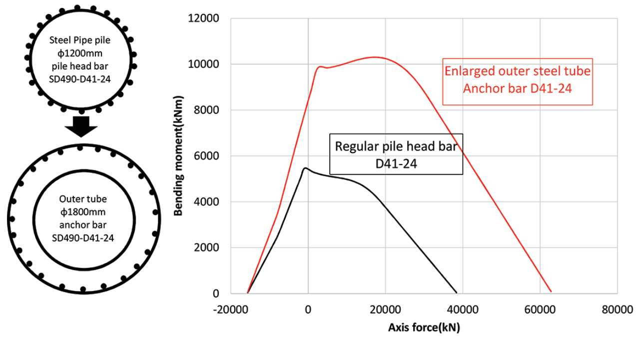

Fig. 9 Improvement of bending capacity using enlarged outer steel tube

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