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Special Contribution

The technological transition of steel pipe piles, tubular sheet piles, and steel sheet piles

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The current technology of steel pipe piles, tubular sheet piles, and steel sheet piles has been developed through continuous efforts with trial and error by various parties concerned to meet the demands of the times. On the occasion of the 50th anniversary of the Japanese Technical Association for Steel Pipe Piles and Sheet Piles in August 2021, the technological transition of steel pipe piles, tubular sheet piles, and steel sheet piles from the end of World War II to the present was compiled. In this article, I would like to briefly introduce the transition from the aspects of product, construction, and design.

1. From wood to steel

(1) Shift from wooden piles to steel piles

Table 1 shows the major changes in steel pipe piles, tubular sheet piles, and steel sheet piles from the post-World War Ⅱ period to the present. Before the war, the mainstream of foundation piles in Japan was wooden piles, mainly pine piles.

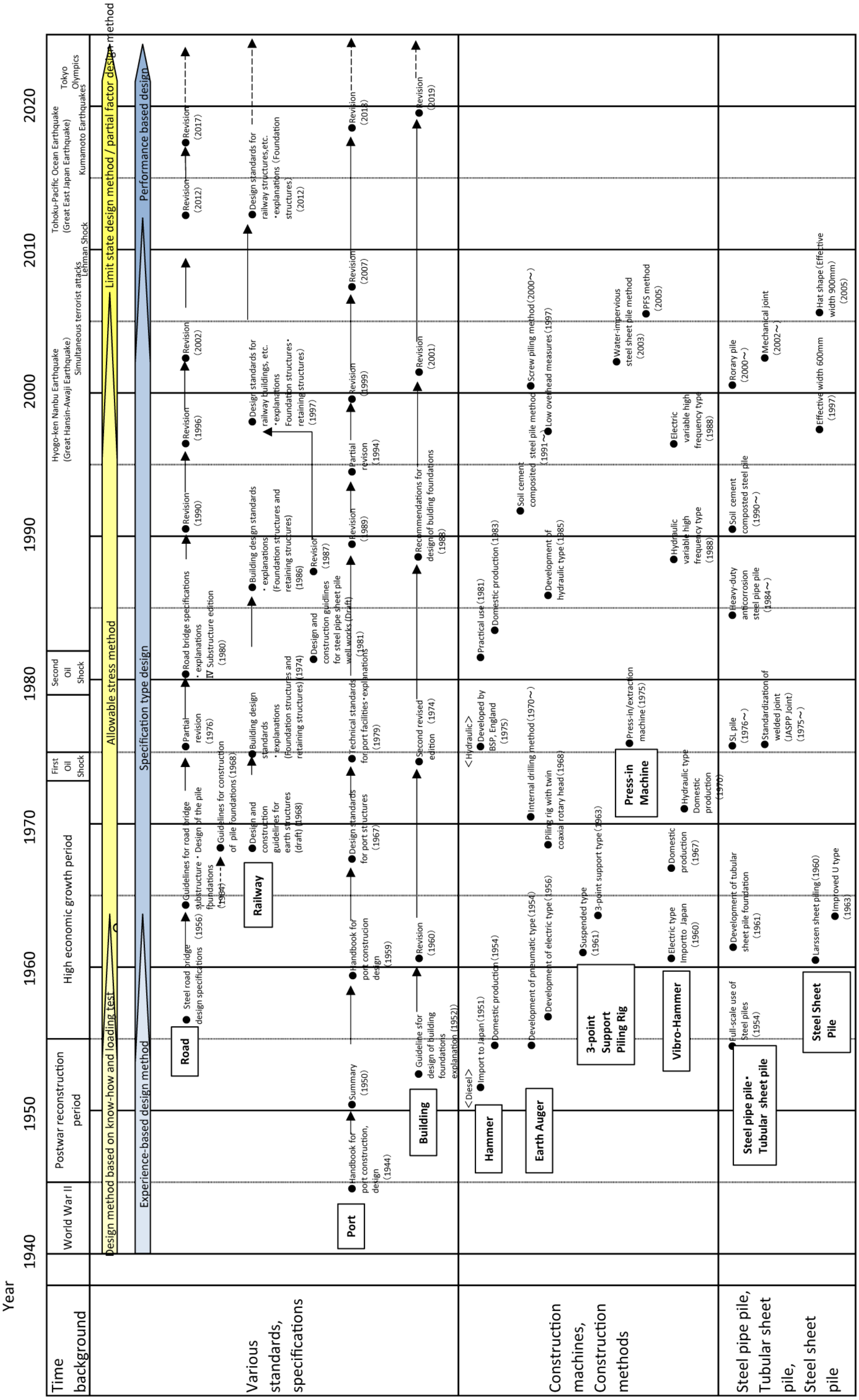
Under such circumstances, in 1954 after the war, the Second Port Construction Bureau of the Ministry of Transport (currently the Tohoku Regional Development Bureau of the Ministry of Land, Infrastructure, Transport, and Tourism) used steel pipes as foundation piles at the Shiogama Port pier. Since this case, during the period of high economic growth when urban development and social capital development rapidly progressed, a large number of steel pipe piles became to be used as foundations for road bridges and buildings, including port structures[1] . This was due to the depletion of timber as well as the protection of natural resources[2], but in addition to the fact that precious steel materials which had been used for military purposes during the war became to be distributed to the market, in Japan which is an earthquake-prone country, in response to the needs for urban formation (construction of large heavy structures, securing of seismic structures) mainly in coastal areas with a lot of soft ground, it was considered that the features of the steel pipe piles were suitable for construction with longer piles because the stiffness of steel materials was higher than that of wooden piles, and the horizontal resistance and bearing capacity were also large.

Steel pipe piles have been developed according to the application to meet various construction conditions. For example, in the 1970s, SL piles (Photo 1) were developed against the negative skin frictional force that tended to occur in soft ground and landfills. SL piles are piles in which a special asphalt (Slip Layer compound) was applied to the surface of a steel pipe as a slip layer, and the slip layer material behaves like a viscous body under a load that acts over a long period. However, it has the property of behaving like an elastic body (viscoelastic property) against a load acting in a short time. In addition, in the 1980s, the problem of corrosion of steel structures that had been constructed up to that point became apparent, so the development of various corrosion countermeasure technologies, including heavy-duty anticorrosion steel pipes (Photo 2), began at full scale.

Photo 1 SL Piles[3]

Photo 2 Heavy-duty anticorrosion steel pipe pile with polyethylene coating (Black part is the covering material)

Table 1 Major changes in steel pipe piles, tubular sheet piles and steel sheet piles



In the 1960s, the development of tubular sheet pile foundations using tubular sheet piles as well as steel pipe piles started. The tubular sheet pile foundation is an elastic foundation, where the tubular sheet piles are installed in a good quality bearing layer in a combination of circular, oval, or rectangular closed shapes, the inside of the junction pipe is filled with mortar, and its head is rigidly bonded by the top plate so that horizontal resistance and vertical bearing capacity to design loads can be obtained (Fig. 1). The idea of the tubular sheet pile foundation originated from the construction of bridge foundations and dolphins by the Paine Company in the former West German using Box Pile called Paine Pile in 1930. Development of this foundation started in 1961, in 1967 as a large blast foundation, and in 1969, it was first adopted for the Ishikari Kakoh Bridge as a bridge foundation.

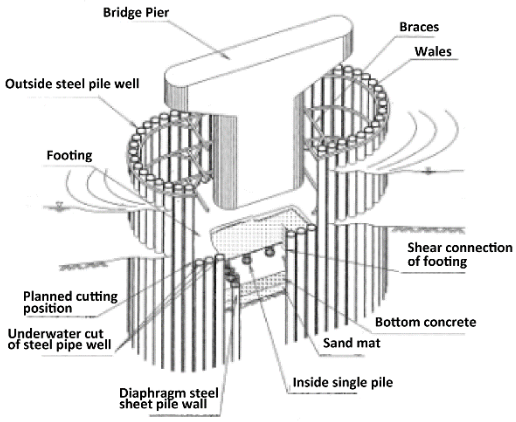


Fig. 1. Schematic diagram of tubular sheet pile foundation for temporary cofferdam

(2) Shift from wooden sheet piles to steel sheet piles

As with steel piles, wooden sheet piles made of pine wood were mainly used in the early days. Wooden sheet piles had many drawbacks, not only in terms of cross-sectional strength and durability but also in that it took time to process the part that was to be the interlock and that the interlocked part was not tightly sealed, therefore it was mainly used for earth retailing of small-scale excavation construction. In the 1930s and 1940s, as the scale of construction work increased, high-rigidity earth retaining walls became necessary, and the sheet pile construction methods using reinforced concrete were often used for small quays and river revetments in many cases. Even in the case of reinforced concrete sheet piles, it was difficult to secure the water tightness of the interlocks as in the case of wooden sheet piles, so there were also inconveniences such as that it was not suitable for places where water flowed in and out, and that a large machine was required for construction. Steel sheet piles emerged as materials with features such as "high strength, workability, rapid construction, and tightness of interlocks" that would make up for some of the shortcomings of wooden sheet piles and reinforced concrete sheet piles.

Photo 3 Hat-shaped steel sheet pile[6)]

In 1923, the Great Kanto Earthquake struck Japan, causing great damage. A large number of steel sheet piles were imported from all over the world for quick recovery from the disaster (especially in the harbor and river fields). This incident is considered to be a breakthrough in the steel sheet pile method [5)]. In 1931, the steel sheet piles with an effective width of 400 mm were produced for the first time in Japan, and they were widely used for the promotion of port facilities during the postwar reconstruction period. In the 1960s, steel sheet piles with an effective width of 500 mm were developed, and in the 1990s, wide steel sheet piles with an effective width of 600 mm were developed. In 2005, to respond to speeding up of public works, cost reduction, and labor-saving, manufacturing of the hat-shaped steel sheet piles (Photo 3) with an effective width of further widened 900 mm widths was started.

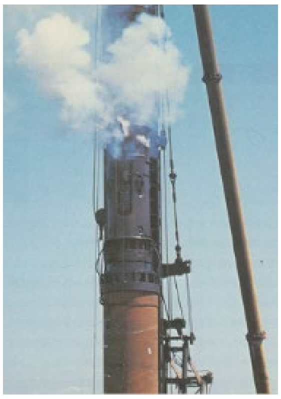
2. Technical transition of construction method and construction management

(1) Impact Driving Method

As with steel sheet piles, the method of driving steel pipe piles was mainly Impact Driving Method. Before the 1970s, it was common to drive piles and sheet piles by driving with human power, and a drop hammer (Monken) was used to lift the weight with a winch or the like and let it fall freely (Photo 4 (a)) [1)] After the 1890s, drop hammers powered by steam engines were introduced to Japan, and steam hammers were domestically produced in 1929 [7)]. Since the steam hammer (Photo 4 (b)) used steam or compressed air as the driving power source, it had the features that the construction speed was faster and the driving force could be adjusted compared to the construction by free fall using the drop hammer. After World War II, due to the development of a diesel hammer (Photo 4 (c)) with even higher construction capacity, this became the mainstream of Impact Driving Method. A diesel hammer was developed by DELMAG of Germany in 1938 and imported to Japan in 1951. After that, it was domestically produced in 1954, and domestic machines have been developed one after another since 1960 [2)]. While the construction capacity of the diesel hammer was high, there was a problem that a loud noise was generated and oil smoke was contained when the exhaustion was made. Under such circumstances, public awareness of pollution, which had become a social problem since the 1960s, increased, and the development of construction methods that would suppress noise progressed even in pile driving work. This is how the "soundproof cover construction method" (Photo 4 (d)), which covered the diesel hammer with a soundproof cover, was developed. As a result, not only the noise generated during pile driving was reduced, but also the scattering of oil smoke was reduced. After that, hydraulic hammers (Photo 4 (e)), which were less noisy than diesel hammers and did not scatter oil smoke, began to be adopted, which has led to the current Impact Driving Method.


(a) Drop hammer[8]


(b) Steam hammer[8]


(c) Diesel hammer[9]


(d) Soundproof cover construction method[10]


(e) hydraulic hammer[11、12]

Photo 4 Transition of Impact Driving Method (Impact Hammers)

(2) Low Noise Piling Method (Vibro-hammer Method, Internal Drilling Method, Press-in Method)

Regulations on noise and vibration became stricter due to the enforcement of the law, making pile driving construction by the hammer in urban areas practically difficult. Compared to diesel hammers, although hydraulic hammers were less noisy and did not scatter oil smoke, more effective low noise and low vibration construction methods have been further required in urban areas.[13]. Therefore, as a construction method to reduce noise and vibration during construction, in cooperation with pile construction companies and tubular pile makers, the development of the Press-in Method has been promoted along with hydraulic construction machines (press-in machines), the embedded pile construction method (Internal Drilling Method, Pre-boring Pile Construction Method) and the vibration construction method by Vibro-hammer (Vibro-hammer Construction Method). [1]

1) Internal Drilling Method

In the case of the Internal Drilling Method, an auger screw is inserted into the hollow part of the steel pipe pile using a 3-point-support pile driving rig (Photo 5), and the soil at the toe of the pile is removed while excavating the ground and install the steel pipe pile to the specified depth. It is roughly divided into three methods according to the treatment method of the pile toe ((1) Cement Slurry Mixing Method, (2) Final Impact Driving method, and (3) Concrete Placing Method). One of them, the Cement Milk Spouting Stirring Method, is the mainstream of the Internal Drilling Method, that is after the pile reaches a predetermined depth, cement milk is spouted from the auger tip to produce enlarged base pile protection.

Photo 5 3-point support pile driver rig[15)]

2) Vibro-hammer Method

Vibro-hammer was developed in 1934 under the guidance of Dr. Balkan of the Soviet Union, and is said to have been used for construction work after World War II[14)]. Please refer to Fig.2 for the principle of penetration and extraction of the Vibro-hammer method. In general, when the soil is vibrated, the bonds between the soil particles that make up the soil temporarily decrease. Driving of the pile by the Vibro- hammer utilizes this phenomenon, that is, driving the pile utilizing the pile weight (Wp) and the weight of the Vibro-hammer (W) that exceeds the pile toe dynamic resistance (Rv) while loosening the shaft friction of the pile by vibration caused by the Vibro-hammer. There are two types of Vibro-hammers: the electric type (Photo 6 (a)) and the hydraulic type (Photo 6 (b)).

In 1960, 50 electric Vibro-hammers were imported at a stroke from the Soviet Union, which was then a developed country of Vibro-hammers, to drive steel sheet piles in the ground used as earth retaining walls. With this, the major flow of Vibro-hammer development began [1), 2)]. The hydraulic types were domestically produced in 1970, and the electric types were domestically produced from 1967 to 1973. The Vibro-hammer has been improved since then; the hydraulic variable high frequency vibro-driving machine type was developed in 1988, and the electric variable high frequency vibro-driving machine type was developed in 1996. They are still widely used when building steel pipe sheet pile foundations. In the Vibro-hammer method, as a method to reduce noise and vibration during construction, there are cases where a jet pipe is installed on the pile, and jet water is ejected from multiple nozzles at the pile toe to drive the pile. (JV method).

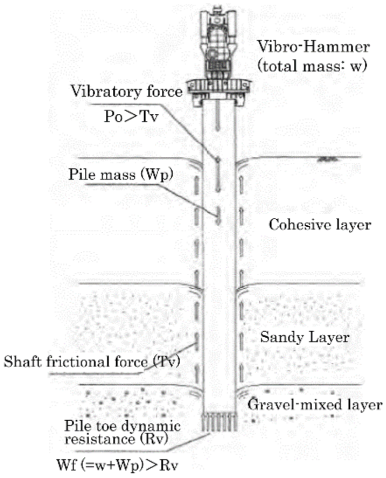


Fig. 2. Construction Principle Diagram of Vibro-Hammer[14)]

(a) Electric[16)]

(b) Hydraulic[17)]

Photo 6 Vibro-hammers

3) Press-in Method

The Press-In Method is a low-vibration, low-noise method mainly used when constructing steel sheet pile walls and tubular sheet pile walls. In Japan, a press-in machine for steel sheet piles was put into practical use in 1975, which was about the same time as the vibration regulation law was enforced in 1976, and then around 1990, a press-in machine for steel pipe piles was put into practical use.

The press-in method requires a reaction force for press-in, and as a method to secure it, i) the method using the load of heavy objects (Weight method), ii) the pile/sheet pile extraction resistance during construction is used. (Extraction resistance method), iii) A method of press-in/extracting the next pile/sheet pile into the ground with a static load by hydraulic pressure using the extraction resistance of the pile/sheet pile that was previously installed. (Reaction piling method, Fig. 3), and so on.[18]. The Reaction piling method has the following features in addition to the features of low noise and low vibration.

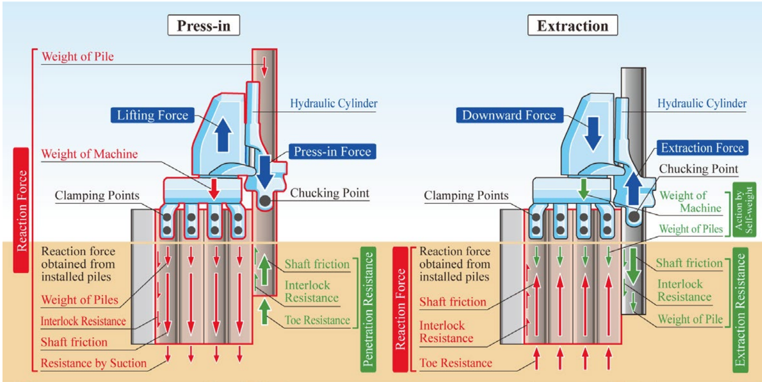


Fig. 3. Reaction force and resistance force acting during press-in/pulling-out using the reaction force piling method[18]

(1) Construction which does not require a vast construction yard is possible

As shown in Fig. 3, since construction utilizing a compact machine is possible, it does not require a vast construction yard and construction in a limited space is possible. Since the press-in machine walks on the previously installed pile/sheet piles by itself, it is possible to carry out the construction with only one crane for suspending the pile/sheet pile and pitching it in the construction machine. The "non-staging system" can be applied when there are various restrictions in places where temporary scaffolding cannot be constructed such as on slopes and water away from land. As shown in Fig.4, the non-staging system is a series of processes in which all the construction machines required for press-in are placed on the pile/sheet piles that were previously installed and move by themselves and carry out the process where the pile/sheet piles are transported, pitched, and installed. As a result, temporary-less construction can be realized, and construction can be performed even under severe construction conditions subject to various restrictions such as on slopes and water away from land.

(2) Application to various ground conditions is possible.

By using the driving assistance for the press-in method of the Reaction Piling Method, it becomes possible to construct under various ground conditions. For example, it is possible to press-in steel sheet piles and pipe sheet piles by using a water jet for densely compacted sandy ground and using an auger for harder ground such as gravel layers and layers containing a large number of cobbles. For underground obstacles such as ground with huge stones and reinforced concrete, there is the Rotary press-in piling method in which a special press-in machine presses into the ground and penetrates through obstacles by rotating a steel pipe pile with a bit at the toe.

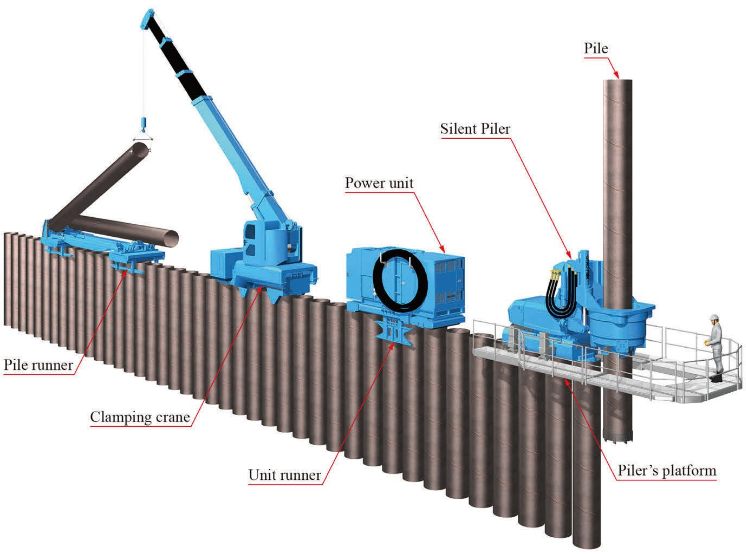


Fig. 4. Non-staging System [18]

(3) Development of high bearing capacity piling methods (Soil-Cement Composited Steel Piling Method, Screw Piling Method)

In Japan, as large-scale structures began to be planned and constructed in various fields, there has been an increasing need for a construction method that can secure bearing capacity and suppress soil discharge compared to the Internal Drilling Method. In response to such needs, high bearing capacity pile construction methods with excellent bearing capacity performance such as the Soil-Cement Composited Steel Piling Method and the Screw Piling Method have been developed.

1) Steel Pipe Soil Cement Pile Method

The Steel Pipe Soil Cement Pile Method (Photo 7) is a synthetic pile construction method in which, by applying ground improvement technology, cement milk of predetermined composition is injected into the original ground from the tip of the excavation stirring head, and then unify it by penetrating a steel pipe with outside protrusions (ribs) (Fig. 5) in the soil cement column created by mixing and stirring. It is possible to reduce the amount of soil discharged from the construction of soil-cement columns by utilizing the local ground[19,20], and there are also advantages such as being able to divert it to roadbed materials after solidification. In addition, since the protrusions (ribs) on the outer surface enhance the adhesion to the soil cement column for unification, the bearing capacity can be evaluated by the diameter of the soil cement column.

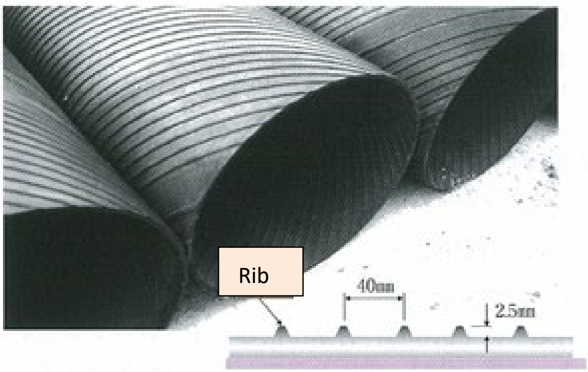


Fig. 5. Steel pipe with outside protrusions (ribs)[21]

Photo 7 Steel Pipe Soil Cement Piler[15]

2) Screw Piling Method

(a) Open-end type

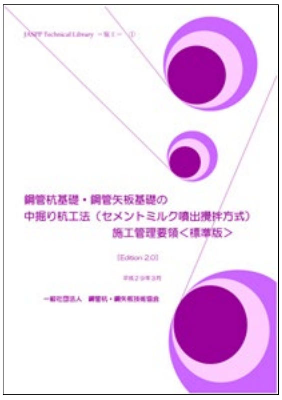
(b) Flat type

Photo 8 Tip blades of the Screw Piling Method

The Screw Piling Method has been put into practical use since around 2000. The Screw Piling Method is a method that realized low noise and low vibration without generation of soil discharge, which was not solved by the Internal Drilling Method and the Steel Pipe Soil Cement Pile Method. Similar to the characteristics of the Impact Driving Method, it is possible to manage the construction through the pile body. As shown in Photo 8, the Screw Piling Method is a method in which a spiral blade or a steel pipe pile obtained by welding two steel plates to the toe of a steel pipe is rotated and penetrated into the ground by the propulsive force of the blade at the toe of the pile. There are two types, an open-end type, and a closed-end type. The construction method is classified into two types according to the pile diameter. If the steel pipe diameter is a small or medium diameter of about ϕ600 mm or less, construction is made using the rotary drive device installed in the Photo 5 3-point pile driving machine to apply a rotational force to the pile head, and if the steel pipe diameter is ϕ600 mm or more, construction is made using the body rotation method that applies rotational force to the steel pipe body with an all-around rotating machine. The Screw Piling Method is highly applicable to battered piles, and its adoption cases are increasing.

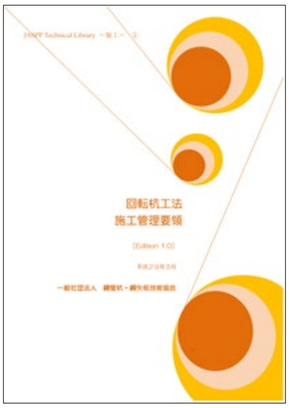
3) Construction Management

The main activities of the Japanese Technical Association for Steel Pipe Piles and Sheet Piles have been mainly organizing the standards in terms of materials, structures, and construction methods, but to become stricter on construction management and quality control in structural foundations in each field and respond to the transition to the reliability design method which will be described later, we are now tackling various issues related to construction technology and construction management, focusing on "construction" that affects the performance and quality of piles. For example, we have created and published the construction management guidelines (Figs. 6 (a) to (d)) for the Internal Drilling Method, the Screw Piling Method, the Steel Pipe Soil Cement Pile Method, and the Impact Driving Method which was introduced so far, and have made a great contribution to the realization of pile construction with high reliability. In addition, we have established a private-sector qualification named the "Steel Pipe Pile Construction Manager", and are contributing to the training of construction managers such as chief engineers or pile construction managers who have a wider range of advanced abilities in the steel pipe pile construction method.



(a) Internal Drilling Method

(b) Steel Pipe Soil Cement Pile Method



(c) Screw Piling Method

(d) Impact Driving Method

Fig. 6. Guidelines of construction management of each method

3. Transition of design standards

As mentioned above, steel pipe piles, tubular sheet piles, and steel sheet piles began to expand their fields of activity during the period of high economic growth after the war. In addition to reflecting technological progress, users' requests, and efforts in the production by manufacturers, and design standards in each field have been reviewed due to the effects of disasters such as earthquakes. Here, I would like to introduce the main points regarding the transition of design standards.

(1) Transition to the Limit State Design Method and the Partial Factor Design

The Hyogo-ken Nanbu Earthquake that occurred at 5:46 am on January 17, 1995, which was later called the "Great Hanshin-Awaji Earthquake", caused enormous damage to the wide area of the Kinki region. It was one of the largest earthquakes at that time, and the damage to the city of Kobe near the epicenter, shocked not only Japan but all over the world as a disaster in the modern city which was the largest port in the Orient. The Hyogo-ken Nanbu Earthquake had a great impact on various fields such as roads, railways, ports, rivers, and buildings, and affected the subsequent design standards. In the field of roads and railways, the seismic design based on the Seismic ductility design procedure** has been developed in addition to the conventional design by the seismic intensity method based on the allowable stress. In the port and harbor field as well, major revisions were made based on the design system that allowed plastic deformation of steel pipe piles. As a response to the problems that arose while the results of designing by the conventional allowable stress method were accumulated, it was during this period when the development of the limit state design method, adopting the partial factor design method, considering uncertainties in the design as rational design method mainly in the field of superstructures was introduced and also the transition of the design standards for the foundations was made along with the superstructures after the 1990s[22)]. Please refer to Table 2 for when the transition of the design standards for foundations in each field to the limit state design method and partial factor design method was made.

** The Seismic ductility design procedure: A pseudo-static design method often used in Japan, in which the relation between the seismic capacity of foundation and its residual deformation is verified, by taking into consideration the absorbing capacity of dissipating energy due to plastic deformation of the foundation.

Table 2 When the transition of the design standards in each field to the limit state design method and partial factor design method were made[22)]

Design standards	Transition Year
Design standards for railway structures and explanations (Foundation structures)	1997
Recommendations for design of building foundations	2001
Technical standards and explanations for port facilities	2007
Road bridge specifications / explanation IV substructure edition	2017

(1) Introduction of performance design concept

As shown in Table 3, the concept of performance design was introduced in the fields of roads, railways, ports, and architecture in the 2000s [22)]. This seems to have been largely due to requests from society rather than the technical side, such as the promotion of performance standardization of international standards by the International Organization for Standardization (ISO)[23)]. Performance design is the idea of fulfilling the requirements of a structure and confirming the performance by a method with appropriate reliability. [22)]. The performance-based design method is being further promoted in each field based on the damage situation caused by the Kumamoto earthquakes that occurred in 2016.

Table 3 When the concept of performance design in each field was introduced[22)]

Design standards	Introduction Year
Guidelines for building foundational structure designs	2001
Road bridge specifications / explanation IV substructure edition	2001
Technical standards and explanations for port facilities	2007
Design standards for railway structures and explanations (foundation structures)	2012

4. Conclusion

This paper introduced the technological transition of steel pipe piles, tubular sheet piles, and steel sheet piles from the aspects of the product, construction, and design, although it was rather concise due to the page limitation. Since the period of high economic growth after World War II, Japan has developed a huge amount of infrastructure in the fields of roads, railways, ports, etc. Now that more than 50 years have passed since then, the aging of those existing structures has become apparent and it is necessary to take measures. We believe that the press-in method is one of the construction methods that is expected to play an active role as a reinforcing foundation pile for existing structures. This is because, as mentioned above, since construction can be made by a compact machine, it is possible to perform pile installation even under severe construction conditions such as proximity construction and overhead restrictions, which are difficult with a 3-point pile driver. At present, the press-in method is not adopted as a standard method in the Japanese Road Bridge Specification, but we expect that in the future it will become the standard construction method to be used as a reinforced foundation pile in addition to new structures by accumulating data on the required performance. You might find some parts insufficient in this paper, but we hope that this paper will be of some help so that steel pipe piles, tubular sheet piles, and steel sheet piles may make some contribution to the national land resilience in various fields in the future.

REFERENCE

1) Yamashita, H., Hirata,H. and Kinoshita, M. (2010): Challenges in the past and future of design and construction technologies on steel pipe piles in Japan, Journal of JSCE F, Vol.66, No.3, pp.319-336. (in Japanese).

2) Aoyanagi, H. (2008): Technical changes and current issues of construction machinery for foundation works, Kisoko (The Foundation Engineering & Equipment, Monthly), Vol.36, No.3, pp.5-11. (in Japanese).

3) Japan Association for Steel Pipe Piles (1984): Constructing Tomorrow, No.46, p.3. (in Japanese).

4) Research Committee on Corrosion Prevention and Repair Method: Technical information (https://www.bouhoken.com/info/) (in Japanese), accessed on March 3, 2021.

5) Ishiguro, T. (1984): Steel sheet pile method (book1), Sankai-do, 339 p. (in Japanese).

6) Nippon Steel Corporation: https://www.nipponsteel.com/product/construction/list-construction/06.html, (in Japanese), accessed on June 1, 2022.

7) Isohata, H. (2003): Historical study on iron pile foundation and screw piles, Journal of JSCE, No.744/Ⅳ-61, pp.139-150. (in Japanese).

8) GIKEN, LTD. : The museum of piling machines, https://www.giken.com/ja/mission/scientific_verification/the_museum_of_pile_drivers/, (in Japanese), accessed on March 3, 2021.

9) Japan Association for Steel Pipe Piles (1973): Constructing Tomorrow, No.7, p.5. (in Japanese).

10) Japan Association for Steel Pipe Piles (1975): Constructing Tomorrow, No.16, p.7. (in Japanese).

11) Nippon Sharyo (2002): Catalog, Hydraulic hammer NH-B series. (in Japanese).

12) TC-Japan: Hydraulic hammer, http://tc-japan.co.jp/data_04 (in Japanese), accessed on March 3, 2021.

13) Japan Technical Association for Steel Pipe Piles and Steel Sheet Piles (2009): Steel Pipe Piles – Design and Construction -, 603 p. (in Japanese).

14) Technical Research Association for Vibro-hammer Method (2015): Handbook of design and construction of vibro-hammer method, 158 p. (in Japanese).

15) Examination Committee of Construction Manager of Steel Pipe Piles: Reference document, http://www.sppshiken.com/ ？ page_id＝12. (in Japanese), accessed on March 3, 2021.

16) Chowa Kogyo Co. LTD. (2008): Catalog, Electric type Vibro-hammer, Zero VR, Zero MR series.

17) Chowa Kogyo Co. LTD. (2016): Catalog, Hydraulic type Vibro-hammer, Zero SR-series.

18) International Press-in Association (2021): Design and Construction Guidelines of the Press-in Method, 2nd print, 241 p. (in Japanese).

19) Japan Institute of Country-ology and Engineering (2012): Report on Technical Evaluation for HYSC piles (Steel Pipe Soil Cement Piling Method) (in Japanese), 154 p.

20) Japan Institute of Country-ology and Engineering (2006): Report on Technical evaluation for Gantetsu piles (Steel Pipe Soil Cement Piling Method) (in Japanese), 179 p.

21) Okahara M. (2013): Recent trend of manufacture and construction technology of steel pipe piles, Kisoko (The Foundation Engineering & Equipment, Monthly), Vol.41, No.2. p.6. (in Japanese)

22) Japanese Geotechnical Society (2013): Introduction to bearing capacity of deformation of foundation, Introductory series 39, 271 p. (in Japanese).

23) Sugiyama, H. (2004): Fundamental knowledge and application of bridge design based on performance-based design, civil-eye.com web seminar. (in Japanese).

◆ A brief CV of Mr. Tomoyuki Suzuki

After graduating from Saitama University in 2003, Mr. Suzuki joined Kubota Corporation, where he has been engaged in demand development for steel pipe piles and technical review work related to design and construction. Since September 2014, he has been participating in the activities of the Japanese Association for Steel Pipe Piles (JASPP), mainly in the Road and Railway Technical Committee. Currently, in addition to being the head of the Steel Pipe Sheet Pile Team of the Technical Committee for Roads and Railways, he is also the head of the Public Relations Working Group, which provides information on the technical activities of the JASPP regarding steel pipe piles, steel tubular sheet piles, and steel sheet piles.