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Development and Application of Sat-in Pile Foundation

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Abstract

Conventional pile foundations for plant equipment such as frame structures are designed with a concrete footing and ground beams connecting each. Therefore, the construction process depends on on-site labor, since it involves formwork, re-bar work and concrete pouring at the site, which means there are numerous work stages and requires long construction time. The Sat-in Pile Foundation has been developed by Nippon Steel & Sumitomo Metal Corporation, capable of saving labor required concrete works at site, achieving efficiency and shortening construction term. This paper introduces the developed pile foundation, composed of just one steel pipe pile with protrusions on the inner surfaces and filling concrete for one column.

1. Introduction

In the case of the pile foundations of support structures of many plant buildings and equipment, the footing and the ground beams connecting each footing are generally constructed at the top end position of the pile. As the construction work involves many on-site labor works such as the formwork, re-bar, and the concrete pouring work, the construction work requires numerous work stages and construction terms. Therefore, the construction work has become labor-dependent-structured.

On the other hand, the on-site labor cost has increased since the 1990s due to the aging of skilled workers and the shortage of young workers. Therefore, with the aim of reducing the construction cost and shortening the construction term, Nippon Steel & Sumitomo Metal Corporation has developed the Sat-in Pile Foundation. This is a joining method of a column and a foundation steel pipe pile in which the inside of the steel pipe pile is filled in with concrete after the column is inserted into the steel pipe pile through its head. This structure acquired the certification of the Building Center of Japan in 2003 as Sat-in Pile Foundation (Certification No. BCJ Certification-FD0061-01)¹⁾ and has been applied to more than 20 in-company and outside company projects. This article reports the designing method, loading test results, actual applications and the effects of the Sat-in Pile Foundation.

2. Outline of Sat-in Pile Foundation 2.1 Outline of construction method

The construction method of the Sat-in Pile Foundation (hereinafter referred to as "SIPF") consists of three elements of the steel column, filling concrete (not reinforced) and the steel pipe pile as shown in **Fig. 1**. To construct the structure that transfers the load from the upper structure securely, the steel column is inserted into the steel pipe pile, which is filled in with concrete. For the steel pipe pile, the internally-ribbed steel pipe pile (specified in JIS A 5525 Annex A) is used to secure the bonding of the concrete to the steel pipe pile to strengthen the integrity of the steel pipe pile and the concrete. This steel pipe is produced by the spiral pipe forming method as shown in **Fig. 2**, using the rolled coiled steel strip sheet that has the ribs standing 2.5 mm high or above and arranged at intervals of 40 mm or less as shown in **Photo 1**.

2.2 Characteristics of SIPF

In SIPF, as the column has to be incorporated into the steel pipe pile, the size of the steel pipe pile becomes larger than that of the conventional structure. However, the number of steel pipe piles can be reduced. Additionally, not only the labor-dependent type soil work and the concrete work (formwork, re-bar work), but also the volume of excavation are reduced (**Table 1**). As a result thereof, a 30–40% shortening of the construction term and a 20–30% reduction of the total cost of the foundation construction as shown in **Fig. 3** can be realized (based on actual results of in-company construc-

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Photo 1 Steel pipe with inner ribs and the detail

tion). Furthermore, as the land occupancy area is smaller than that of the footing type foundation, the application to the site where the construction area is confined and/or to the slope as shown in **Photo 2** is possible.

2.3 Subject in development of SIPF

In the development of SIPF, it is necessary to define the load transfer mechanism from the column to the pile and to establish the evaluation method of the structure design. To avoid providing any application restrictions to the problems in the actual construction, to the upper structures and to the main specification, to maintain the high freedom of structure design is a very important factor in the application to actual projects.

The concept of the abovementioned structure design and our

Table 1 Construction process and estimation of total construction period

| | Conventional method | Sat-in Pile Foundation | |
|--------------------|-----------------------|----------------------------|--|
| Piling | Pile driving | Pile driving | |
| Soil work | Excavation | \downarrow | |
| Concrete work | Rebar arrangement | \downarrow | |
| | Anchor bolt or column | Anchor bolt or column | |
| | setting | setting | |
| | Formwork | \downarrow | |
| | Concrete pouring | Concrete pouring | |
| Soil work | Backfill | \downarrow | |
| Total construction | Pasa | $Pasa \times 60$ to 70% | |
| period | Dase | Dase ~ 00 10 /070 | |



Fig. 3 Estimation of cost reduction



Photo 2 Application on a slope

aims are outlined below, as well as the results of the verification test and the various developed jointing types.

3. Method of Designing

3.1 Concept of load transfer

Figure 4 shows the load transfer from the column of the upper structure to the steel pipe pile. The axial load is transferred to the filled-in concrete via the base plate attached to the bottom end of the column and the axial load is resisted by the concrete restrained by the ribs of the steel pipe pile. The bending moment and the horizon-



Fig. 4 Load transfer in Sat-in Pile Foundation

tal shear load are transferred to the filled-in concrete as the bearing pressure on the outer side of the embedded column, which is restrained and resisted by the hoop-tension of the steel pipe pile. 3.1.1 Design for axial load

In the design for the axial load acting in the direction of pushingin, it is necessary to evaluate the mode of the contingent fracture that may take place in the concrete below the base plate. The modes of the contingent fracture are considered as (1)-(3) below.

- (1) Fracture of the filled-in concrete bearing below the base plate
- (2) Fracture of the filled-in concrete at the bonding boundary of the rib of the inner-ribbed steel pipe and the concrete
- (3) Shearing fracture of the filled-in concrete in the circumference of the base plate

As shown in the figure in the center of Fig. 4, the axial load is considered to disperse in the filled-in concrete within the angle of 45 degrees and is transferred to the steel pipe pile and supported. Therefore, the filling-in length of the concrete is determined first by taking into consideration the length of dispersal, after which, the abovementioned modes of fracture are checked.

As the bonding resisting strength of the filled-in concrete at the rib of the internally-ribbed steel pipe is complicatedly composed of the bearing strength at the rib and other bonding strength, further added by the restraining effect of the hoop tension of the steel pipe, based on the results of the structural tests, the length of the steel pipe pile below the base plate is specified as standard with the sufficient safety margin being 1.5 times or more of the diameter of the steel pipe pile. Regarding the axial load in the direction of pullingout, since the length of the concrete filling above the base plate is important, the same method of design as that applied to the axial direction in pushing-in is applied.

3.1.2 Design for bending moment and horizontal shear load

The load caused by the bending moment and the horizontal shear load forms a compression force distributed on the side of the column in a triangular form as shown in Fig. 4 and becomes the compression force that works to expand the inside of the steel pipe pile via the filled-in concrete, which is considered to be supported by the peripheral force of the steel pipe pile. Therefore, in the design, it is necessary to evaluate the fracture mode of the filled-in concrete caused by the hoop tension of the steel pipe pile. In other words, the following modes of (1) and (2) are considered.

(1) Fracture of the bearing of the filled-in concrete on the side surface of the embedded column

(2) Fracture of the steel material due to the circumferential tensile stress of the steel pipe pile

Details of the abovementioned load transfer and the fracture will be discussed with the results of the structural tests in a later section. **3.2 Geometrical restriction**

3.2.1 Embedded length of column and steel pipe pile

In the conventional design of the embedded supporting leg of the column, as the column supporting leg can transfer the maximum plastic deformation moment and can be treated as the rigid jointing by making the embedded length of the column in the column foundation concrete twice or more of the column height², in SIPF, the length of the column embedded in the concrete is specified as being twice or more of the column height.

3.2.2 Relationship between column height and size of steel pipe pile

In the case that the diameter of the steel pipe pile is excessively large as compared to the column height, as a difference in the load transfer mechanism may exist, based on the range where the load transfer mode mechanism is confirmed by test¹), the diameter of the steel pipe pile is specified as not exceeding three times that of the column height.

3.3 Restricting condition in construction

There is no restriction on the driving method of the steel pipe pile, and this SIPF is applicable to any steel pipe piles driven by the hammering method, inner excavation method and rotary press-in method. However, since SIPF is structured in such a way as to join the steel pipe pile and the column without using footings, the driving accuracy has to be controlled in a range stricter than that of the general case. In SIPF, the deviation of the center of the column from the center of the steel pipe pile is specified as being controlled to within 1/10 D (D: steel pipe pile diameter) or 50 mm.

On the other hand, in pouring concrete in SIPF, it is necessary to pour concrete after the water inside of the steel pipe pile has been drained by a pump and made water-free. Therefore, attention must be paid to the level of the underground water and the penetration of rain water.

4. Structural Test

Structural tests were conducted to confirm the bonding strength between the internally-ribbed steel pipe pile and the concrete, which characterizes SIPF and transfers the axial force, as well as to confirm the performance of the jointing structure that transfers the bending moment and the horizontal shear force. Two types of tests that examined the load transfer of the axial force and the bending moment are introduced below.

4.1 Confirmation of axial force transfer mechanism

To confirm the bonding strength between the internally-ribbed steel pipe pile and the filled-in concrete, the punching shear test was conducted with the procedure as shown in **Fig. 5** and with the test parameters as shown in **Table 2**. The bonding strength τ_u is defined as the value of the maximum load divided by the product of inner circumferential length of the internally-ribbed steel pipe pile and the concrete-filled-in length L (internal area of the internally-ribbed steel pipe pile). In **Fig. 6**, the relationship between τu and the concrete strength F_c is arranged according to the profile of the internal rib. This indicates that τ_u does not rely on the spacing s and/or height h, but rather on F_c . To avoid the bonding of the filled-in concrete becoming essential in the transfer of the axial force, the product of the bonding strength and the bonding area (internal area of the internally-ribbed steel pipe pile), namely, the total bonding strength needs to be larger than the axial load. Since the allowable maximum value

of the axial force is the product of F_c and the area Ac of the internally-ribbed steel pipe pile with concrete, if the total bonding strength is made larger than that, bonding to the ribbed steel pipe does not fracture in advance by axial load. Then, from the formula (1) which satisfies the above, the relationship between the value obtained by the formulae (1) and the ratio of the bonding length L vs. the steel pipe diameter D is shown in **Fig. 7**.

$$\{F_{c} \times (1/4) \pi D_{in}^{2}\} / (\pi D_{in} L \tau_{u}) \le 1$$
(1)

where F_c : standard design strength of concrete (MPa), D_{in} : steel pipe diameter (mm) after subtraction by the pipe thickness and the height of the rib, L: filled-in concrete length (mm), τ_u : bonding strength (MPa). In order for the value on the vertical axis to become 1.0 or below where the bonding fracture does not take place in advance, a bonding length of 1.5 times or larger than the pipe diameter must be secured. From this, in SIPF, as the standard for the filled-in concrete length, it is specified that a length longer than 1.5 times or more of the pile diameter must be secured below the base plate.

4.2 Confirmation of transfer mechanism of bending moment

To clarify the load transfer mechanism and the load bearing capacity of the jointing section when a column is embedded in a steel



Fig. 5 Outline of the punching shear test

Table 2 Case of punching shear tests

| Diameter of steel pipe | D (mm) | 250, 400, 600 |
|----------------------------------|-----------|---------------|
| Height of shear keys | h (mm) | 2.5, 3.0, 4.1 |
| Spacing of shear keys | s (mm) | 36, 40 |
| Compressive strength of concrete | Fcu (MPa) | 25 to 50 |
| Angle of ribs | θ (deg.) | 0, 30, 40 |



Fig. 6 Bonding strength of the interface between concrete and steel pipe with ribs

pipe pile, a test sample of a steel pipe pile of 1 200 mm in diameter \times 9 mm thickness jointed with a steel pipe column of 900 mm in diameter \times 16 mm thickness was built, and a bending test was conducted. As shown in **Fig. 8**, the bending moment acted upon the test sample at four points, namely at the loading points on the jointing section and at the supporting points. In the test, to expedite the fracture at the joint section, the embedding depth was shortened to 1.5 times that of the column height. Furthermore, to prevent the yielding of the column ahead of the fracture at the joint section, the column was filled-in with concrete at the joint-section.

In **Fig. 9**, the relationship between the load and the displacement at point A is shown. The process of yielding at each point is as follows. First, the tensile strain in the axial direction of the steel column of 900 mm in deameter yielded at 2242 kN, followed by the yielding of the tensile strain in the axial direction of the steel pipe pile of 1200 mm in deameter at 2443 kN. Thereafter, the strain in the circumferential direction at the top end of the steel pipe pile of 1200 mm in deameter yielded at 3204 kN. It was confirmed that the load bearing capacity of the joint section is higher than the yielding load bearing capacity of the column and the steel pipe pile and the yielding of the steel pipe pile, the hoop tension of which restrains



Fig. 7 Relationship of concrete length to the failure mode







Fig. 9 Relationship between load and displacement



Fig. 10 Axial direction distribution of the strain in the circumferential direction

the bending moment and the horizontal shear force occurred later than the occurrence of the yielding of the steel pipe pile in the axial direction. From this, it was revealed that as long as the dimensions of the joint section are secured, the joint section is not essential and the ordinary design of the column and the steel pipe pile is acceptable.

Figure 10 shows the distribution in the axial direction of the strain in the circumferential direction of the steel pipe pile of 1200 mm in deameter at the time when the steel column of 900 mm in deameter yielded in the axial direction at the load of 2242 kN. With respect to the center position of the embedded column, as the triangular pattern of the strain distribution of the bottom side of the steel pipe pile takes the opposite form when compared with that on the top side of the steel pipe pile, the column rotates around the center point of the embedded column and the compressive stress developed on the side of the column and distributed in a triangular form is transferred to the pile in a triangular form via the concrete, confirming the appropriateness of the load transfer mechanism shown on the right side figure in Fig. 4.

This test revealed that appropriate designing such as making the embedded length of the column sufficient would allow the embedded column to yield prior to the yielding of the joint section, and also would prevent the joint section from being in a critical state.

5. Joint Type

Many of the plant support structures are designed so as to bear

 Joint type

 Embedded
 Anchor bolt
 Embedded with socket pipe
 Anchor bolt with socket pipe

 Image: Colspan="2">Image: Colspan="2" Image: Cols

horizontal forces with a diagonal brace. In this case, the foot of the column is pin-jointed and axial loads and/or horizontal loads are large, and large bending moments do not occur. Furthermore, with the assortment of only the rigid jointing of the embedded column, SIPF is unable to fully enjoy the advantage of shortening the construction term as the erection of the support structure on-site and the process of fixing the column leg part with concrete are very complicated. Taking this into consideration and with due attention paid to the characteristics of the support structure, the types of joint as shown in **Table 3** have been developed.

Firstly, in terms of jointing structure, there are two types. One is the embedded joint type of rigid jointing of the upper structure with the lower structure; the other type is the anchor bolt joint type of pin-jointing. In SIPF, the column and/or the base plate have to be incorporated into the steel pipe pile geometrically. Therefore, depending on the sizes of the column and/or the base plate, a steel pipe pile whose diameter is larger than that required of a pile has to be used, affording inefficient design. To solve the problem, a socket pipe jointing structure has also been developed: The structure uses a socket pipe made of an internally-ribbed steel pipe having a diameter slightly larger than that of the steel pipe pile to join the column and the steel pipe pile. In this type, for the column leg joint structure, two types of embedded joint and anchor bolt joint are provided and either of them is separately applicable depending on the load on the supporting structures, interactive conditions, dimensional condition and so forth. Thus, rational and efficient design is realized. At the early stage of the development, the object of the development was the steel pipe column. However, applications to the H-section steel column have increased to many applications and SIPF is applicable to both rectangular and circular shaped base plates.

Figure 11 shows the share percentage of the applied joint types and the column types. This indicates that the actual result of the share percentage of the anchor bolt joint type with the H-section steel pile is the highest.

6. Actual Result of Application

6.1 Actual result of domestic application

The one column/one pile structure has been applied to the foundations of many in-company plants such as electrostatic precipitators, silos, and piping and wiring supporting structures that are supported by steel columns. Now the number of the applications has reached well over approximately 20 projects (approximately 360 piles) since 1994 and has contributed to the shortening of the construction term and the reduction in cost.

Table 3 Joint type of Sat-in Pile Foundation



Fig. 11 Past domestic records of Sat-in Pile Foundation



Photo 3 Silo foundation after the Great East Japan Earthquake

In the Kamaishi Works, which suffered major damage from the Great East Japan earthquake, SIPF was applied to the electrostatic precipitator and the fly-ash silo of the domestic power plant of the steel works. No cracks and/or no gap-openings were confirmed on the foundations and on the surface of the post cast concrete on the foundation (**Photo 3**). The steel works in which the subject equipment is installed recorded a seismic intensity of just under six.

6.2 Actual result of overseas application

In the Ichthys LNG Project³⁾ now under construction off Darwin, Australia, operated by INPEX Corporation, SIPF was employed in a great quantity based on their evaluation of the possibility of it realizing non-soil removal construction and labor-saving in the construction work of the foundation. This is because SIPF matched the Australian market, where the environment is strictly controlled and the labor cost is high. Additionally, another aspect of their evaluation is that in the Ichthys LNG Project, the upper structures are prefabricated block-wise to shorten the installation term and the upper structures thermally deform due to the night and day temperature difference. However, the embedded joint type of SIPF is structured so as to absorb the thermal deformation. Until it was decided that SIPF would be employed, efforts were made to acquire the company's understanding and their reliance on SIPF by presenting the application results, discussions over design, invitation to the actual construction site for observation and so forth. Furthermore, even after the decision had been made to employ SIPF, detailed discussions over the structural design and the needs of the alterations of the design due to the site construction conditions were quickly addressed.

7. Future Prospect

SIPF obtained certification by the Building Center of Japan in 2003. However, at the time, the allowable stress design method was in the main stream and the application range was limited. To expand its application to the projects of outside companies, both domestic and overseas, the following problems need to be solved⁴).

- 1) Deign method: switch to the limit state design method (LRFD)
- 2) Scale of structure: correspondence to a pile diameter of 1200 mm or larger
- 3) Certification: acquisition of international certification of a third-party organization

As for 1), although the design method based on the allowable stress design method is established domestically, switching is possible by rearranging the possible fracture mode and by changing over the design formulae to those conforming to the limit state design method.

As for 2), in the domestic certification, the bonding strength without the restraining effect of the steel pile was set. Therefore, it is necessary to establish a formula of bonding strength, taking into consideration the restraining effects of the steel pipe pile to be expressed by the parameters of the diameter/thickness ratio and the profile of the rib inside the internally-ribbed steel pipe pile, by rearranging the past test data and conducting additional tests⁵.

As for 3), efforts are being made regarding the structure and the design method to obtain the Technical Qualification of DNV (Det Norske Vritas: current DNV-GL) that has abundant experience in providing the approval to the design standards of the foundations of a number of jackets and projects^{6,7)}. Currently, the process of acquiring the technical qualification is in the final stage and discussions pertaining to the construction and the provisions of quality control are underway. We hope to obtain the qualification as soon as possible and strengthen the base of SIPF to realize further convenient construction methods.

8. Conclusion

This report introduced the Sat-in Pile Foundation (utilizing internally-ribbed steel pipe pile) that has been developed to respond to the confined construction site, the needs of shortening the construction term and the labor saving on-site in the construction of steel works plants. SIPF is, as illustrated by the example of the Ichthys LNG Project, considered to be effectively applicable to other plant equipment that has similar needs. We are determined to develop the

single pipe pile type and the hybrid structure with a concrete column to make effective use of the steel material through the in-company and outside company projects.

* "Sat-in Pile Foundation" is the registered trademark of Nippon Steel & Sumikin Engineering Co., Ltd.

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