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Authors:	Atsuo Konishi, Structural Engineering Department, NIKKEN SEKKEI LTD Masaru Emura, Structural Engineering Department, Obayashi Corporation
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Structural Design and Construction of the Foundation of TOKYO SKYTREE

Atsuo Konishi[1,†] and Masaru Emura[2]

[1]*Structural Engineering Department, Nikken Sekkei Ltd., Tokyo 102-8117, Japan*
[2]*Structural Engineering Department, OBAYASHI CORPORATION, Tokyo 108-8502, Japan*

Abstract

This paper introduces the structural design and construction method for the foundation of the TOKYO SKYTREE, a new digital broadcasting tower in Tokyo, which has a height of 634 meters. The surface layer of the ground is occupied by soft soil, thus the foundation of this tower is an SRC continuous underground wall pile, designed and developed to have horizontal rigidity and pull-out resistance. The structural integrity and construction method of the wall pile was verified with an on-site full scale pull-out test concluding a maximum load of 40,000 kN.

Keywords: Broadcasting tower, Performance-based design, Foundation design, Construction method, Wall pile

1. Introduction

The TOKYO SKYTREE (Fig. 1.1), completed in February 2012, is a new digital broadcasting tower for the Tokyo Metropolitan area, with a height of 634 m from the ground up and planned as a new quasi-disaster prevention center and landmark of Tokyo.

The site of the tower is occupied with soft ground, with the main constituent layer being silt due to the Sumida and Arakawa rivers nearby. Therefore, the foundation of this tower is an RC continuous underground wall pile. The Podium Pile (Fig. 2.7), which has the same plan as the podium of this tower, has horizontal rigidity in order to decrease displacement of the foundation in instances of strong winds and large earthquakes. Additionally, the Kanae Pile (Fig. 2.7) is a SRC continuous underground wall pile, developed for this project to resist massive uplift forces, harnessing the weight of the rigid soil in the substrate layer. The structural integrity of the Kanae Pile was verified with an on-site full scale pull-out test concluding a maximum load of 40,000 kN.

Figure 1.1. TOKYO SKYTREE^{SM}.

Nikken Sekkei was the structural designer and OBAYASHI CORPORATION constructed the tower. This paper outlines the structural design and construction method for the foundation of the TOKYO SKYTREE.

2. Structural Design of Foundation

2.1. Outline of structural design of superstructure

The tower is part of the development works, the vacant lot of classification yard, which have and part of a 230,000 m^2 building consisting of shops and offices. Each area is divided with EXP.J. structurally from the top of building to the bottom of the foundation because of the differences of their use (Fig. 2.1). The basement of the tower is one story and used as a parking lot.

High performance against strong winds is required for high-rise buildings in Japan because of typhoons that come every summer.[1-5] Similarly, careful seismic design is needed because of the existence of active faults.

Accordingly, a steel structure with a pipe truss was adopted as the structural system for the tower (Table 2.1). The pipe truss is not only light weight and sturdy, which is necessary from a seismic design point of view, but it's also rational in a wind resistant design, decreasing the frontal area and not producing unstable aerodynamics

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[†]Corresponding author:
Tel: +81-3-5226-3042; Fax: +81-3-5226-3030
E-mail: konishi@nikken.jp

Figure 2.1. Divition of this site.

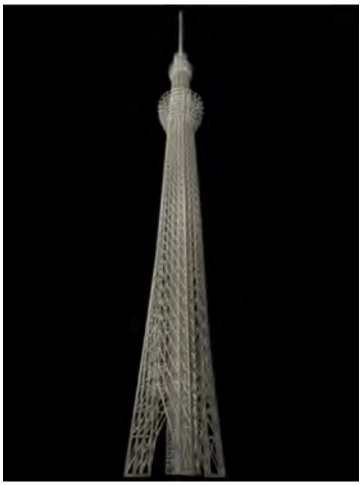

Figure 2.2. Superstructure.

response because of non-existence of outer wall.$^{6-10)}$

Fig. 2.2 and 2.3 show the two types of frame systems coexistent in the tower. One is a lattice framework and the other is a Mega-Truss with a lattice column and girder, the Kanae Truss shown in Fig. 2.3. The coexistence of two frameworks adds structural redundancies and flexibility, allowing room for people in the shopping zone. Furthermore, the Core Column System shown in Fig. 2.4 is a vibration control system for earthquakes and strong winds that was specifically developed and installed for this tower.

2.2. Structural planning of foundation

2.2.1. Outline of ground survey

The site, located at the east end of Tokyo (Fig. 2.5), is part of the Kanto Plain, and is on the bank of the Sumida and Arakawa rivers. Due to the nearby rivers, the surface layer of the ground is occupied with soft soil, the main constituent layer being silt. The structural load bearing layer is a rigid sand-gravel layer at depth of about 35 m from surface of the ground, deposited 20,000 years ago, and with a velocity of shear wave of Vs ≥ 400 m/s. The standard penetration test (SPT) at 120 m, and Microtremor Array Survey (MAS) at 3 km, were carried out. PS-logging was carried out at the same time as the SPT. These sur-

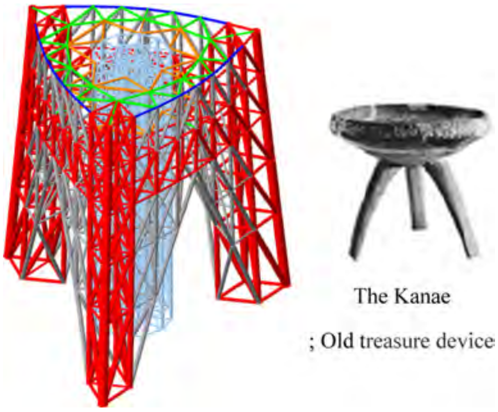

Figure 2.3. The Kanae Truss.

Figure 2.4. The Core Column System.

Table 2.1. Design Criteria of TOKYO SKYTREE

Level	Standards of domestic law	Specification of design for disturbance	Structural safety limit
L1	Rare	Strong wind : Return period= 100 years Earthquake : middle	No damage
L2	Very rare	Strong wind : Return period=1350 years Earthquake : Big	Almost no damage
L3	Unexpected	Strong wind : Return period=2000 years Earthquake : Hidden faults	Elastic behaviour

Figure 2.5. Site of TOKYOSKYTREE®, broadcasting area.

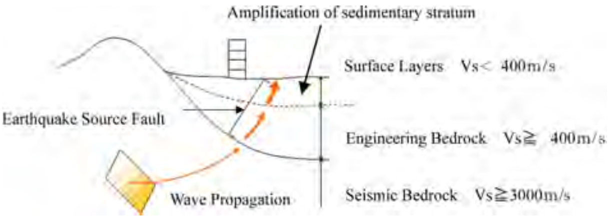

Figure 2.6. Theorized earthquake ground motions.

veys define the analysis model of design earthquake motions and make an accurate seismic design.

2.2.2. Main theme of structural design of substructure

The load bearing layer is relatively deep in depth at 35 m, where the substructure of this tower demanded horizontal rigidity to decrease displacement of the foundation from strong winds and earthquakes. Securing horizontal rigidity is the first topic of foundation design. Therefore, an RC wall 1900 mm thick was placed in the basement floor, and a RC continuous underground wall pile was adopted as a foundation. Both of them have the same plan as the podium of the tower. The RC wall pile is the Podium Pile, shown in Fig. 2.7. Additionally, a cast-in-place pile with expanded pile head was adopted for low-rise buildings of the tower area, which has horizontal rigidity and resistance compared to the general type of pile.

The Kanae Pile, supporting the Kanae Truss, shown in Fig. 2.7, is a SRC continuous underground wall pile, developed for this project to resist a massive uplift force, harnessing the weight of the rigid soil in the substrate layer for pull-out resistance. Securing pull-out resistance and rigidity, both horizontally and vertically, are the second topic of foundation design. Light frames have an advantage against earthquakes, but the uplift load applied to the Kanae Pile exceeded the force obtained by its own weight. That is the reason why the foundation required pull-out resistance. Moreover, the aspect ratio of this tower is about 9, relatively large for a broadcasting tower, and that affects the rocking displacement which affects transmission performance. Therefore, vertical rigidity of foundation has to be controlled, adding extra horizontal rigidity.

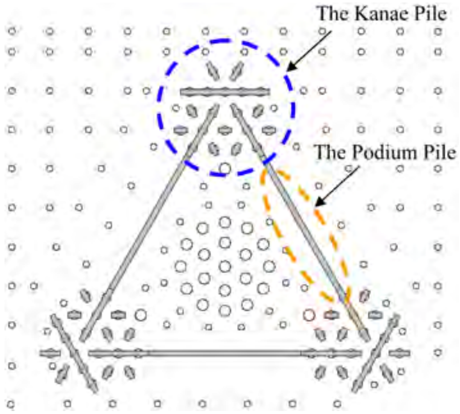

Figure 2.7. Plan of piles.

It is generally accepted that securing both pull-out resistance and the rigidity is difficult in a foundation. When comparative studies about the Kanae pile shown in Fig. 2.8 were started, we found the wall pile plan better than the anchor weight plan. The anchor weight plan obtains pull-out resistance by using own weight and that has definite reliability, but on the other hand the wall pile plan have to addresses several issues, such as reliability of friction between pile and soil or rigidity and strength of the pile.

Finally, it was found that the wall pile plan has an advantage compared with the anchor weight plan at the point of cost and work period. And then, the wall pile plan was adopted as the foundation system of this tower on condition that the several concerns of the wall pile plan would solved by improvement of the structural design and construction methods.

2.3. The Kanae pile

2.3.1. Structural design of wall pile

The wall pile originally had been used as an Earth retaining wall, but recent use in Japan to adopt it have been increasing its use in depths over 50 m. This method of construction gradually acquired reliability as a pile.

The wall pile has in-plane rigidity because of its shape, and the foundation adopting this pile could obtain horizontal rigidity as well if the arrangement of the pile is considered in the design. Therefore, the first topic of the foundation design, to ensure horizontal rigidity, would be solved by use of a wall pile.

The wall pile could use the weight of the soil for pull-out resistance by inserting the pile tip into the rigid layer through friction between its face and soil. The friction has the mechanical characteristic that relative displacemet between pile and soil is under several millimeters until it

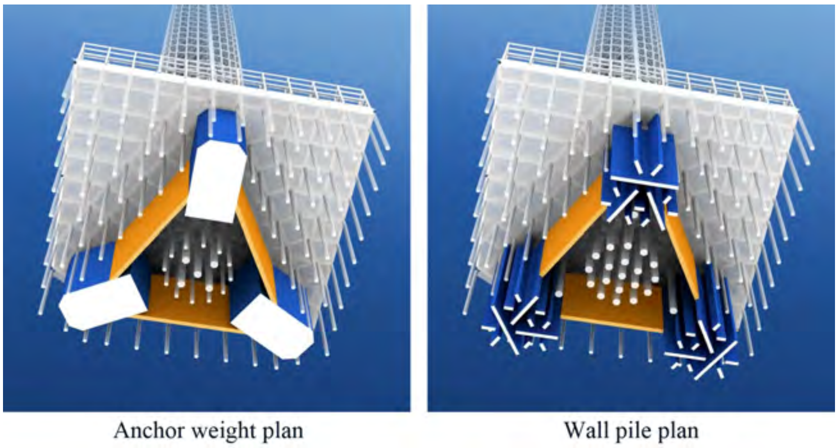

Figure 2.8. Comparative study of the Kanae Pile.

reaches its ultimate value. Using friction, we expect the resistance system of the wall pile will have high virtical stiffness performance.

On the other hand, a general wall pile is an RC structure, and sometimes short steal was insterted as a temporary member. The SRC structure was adopted to the pile body from the tip to the head of it to bear the huge pull-out force, and to impart the force to the steel frame of superstructure (Fig. 2.9).

The wall pile was arranged radially at the Kanae Pile to ensure the surface area of the pile had increased friction, and an SRC girder of depth 5.5 m was adopted for the pile cap.

The length of tip of pile inserted into the rigid layer was 15 m when designed with friction only, but it could be 13 m when a knot is added to the tip of the pile. The support force of the knot couldn't be counted into the strength of the pile because the knot uses bearing pressure which becomes effective after the friction reaches the limit value. However, it could count into the ultimate bearing capacity of pile. That is important for redundancy and reliability of the pile for it to have two different mechanical characteristics.

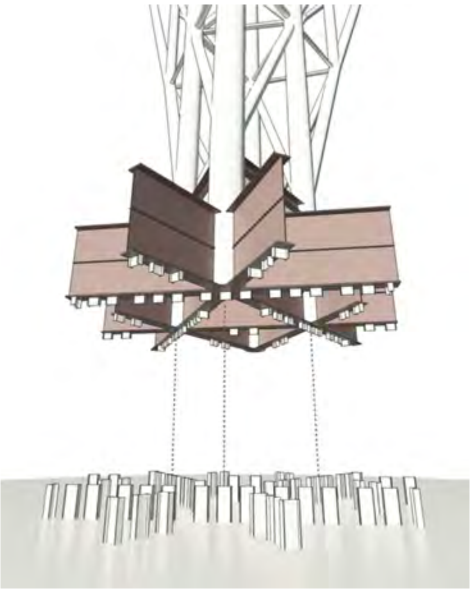

Figure 2.9. Connection between the Kanae Truss and the Kanae Pile.

2.3.2. Pull-out test with full scale pile in the site

It is possible to design the wall pile using common knowledge based on the results of past research, but considering the following point, a full scale pull-out test in the site with a maximum load of 40,000 kN was done, shown in Fig. 2.10.

- This is first time to adopt SRC pile body as a wall pile, from the tip to head.
- The quality of the friction between soil and surface of the pile is usually uneven, so it is effective for accuracy of structural design to do a test using full scale pile compared to a material test.
- It is important to grasp a behavior of RC part of pile

Figure 2.10. Pull-out test of a wall pile.

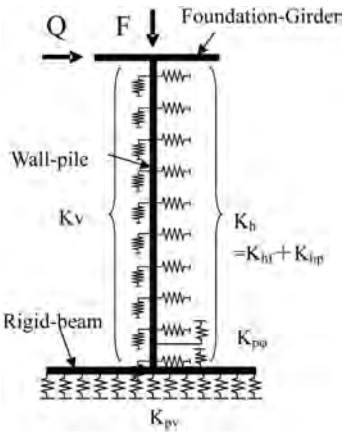

Figure 2.11. Analysis model of pile.

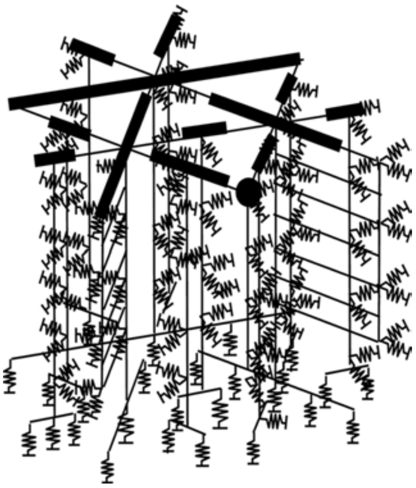

Figure 2.12. Analysis model of the Kanae Pile.

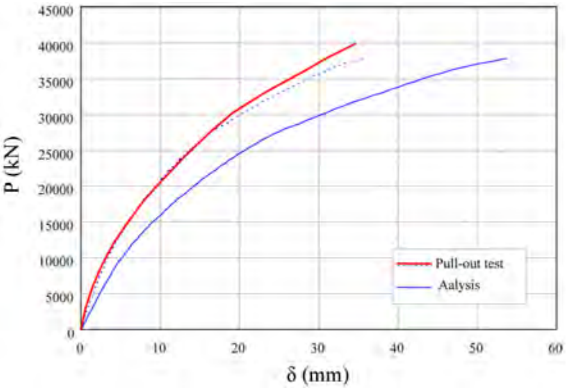

Figure 2.13. Comparison of pull-out test results and load-displacement analysis at the top of the wall pile.

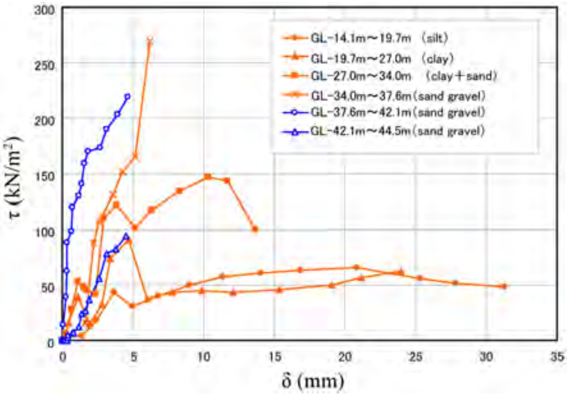

Figure 2.14. Friction-displacement relationship of the pull-out test.

under the pull-out force.

The analysis model for one panel of wall pile and the Kanae Pile were shown in Fig. 2.11 and 2.12. The upper limit of friction as the ultimate value was supposed as an evaluation of the safe side. The result of the pull-out test, load-displacement relationship and friction- displacement relationship are shown in Fig. 2.13 and 2.14. We can see that the analysis of the virtical rigidity of the wall pile is on the safe side with the results of pull-out test. This is caused by the value of upper limit of friction set previously for analysis.

A sensitivity analysis was executed in the phase of structural design using 1 / 2-2 times the standard value as an ultimate friction, and all of the criteria of the tower were confirmed in this study.

3. Construction of Foundation

This section reports the construction of the foundation of the Tower Area which is indicated in Fig. 2.1. In particular, the following explains in detail the construction method of the SRC continuous underground wall pile with knot (the Knuckle wall) developed for this project.

3.1. Main theme of the construction

The following were the main topics of the construction of the TOKYO SKYTREE.

- The construction site was surrounded by railway lines, subway lines, and traffic roads, and is located in a very narrow construction space.
- The construction period of three years and eight months was exceedingly short for a tower of more than 600 m in height in addition to other neighboring new buildings.
- The method to build a reliable wall pile had to be developed so as to bear the huge uplift force and the compressive force in soft ground, and the tensile test was examined with full scale pile to check the workability of the wall pile works.

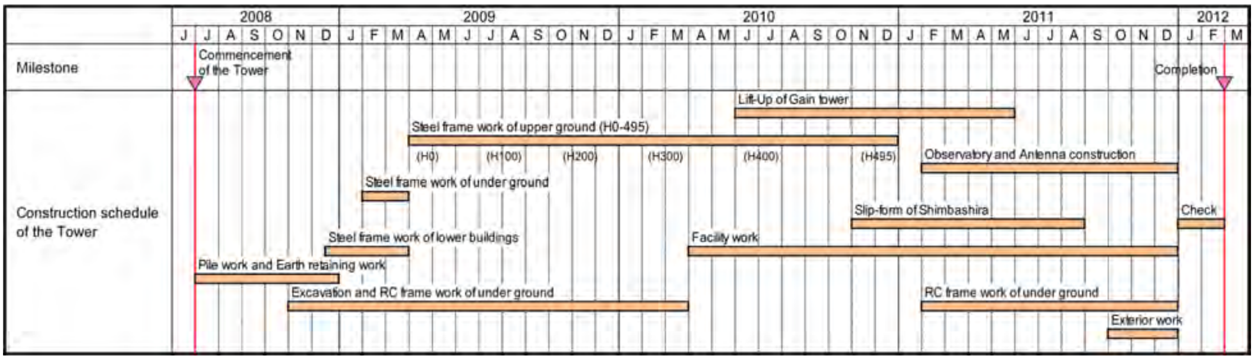

Figure 3.1. Complete construction schedule.

3.2. Outline of whole construction process

Fig. 3.1 indicates the whole construction schedule. The commencement of work was July 2008, and the completion of work was March 2012. The construction period was three years and eight months. In the whole construction schedule, the foundation works and the steel frame works occupied most of the period of time, and the rationalization of these works was particularly important. Fig. 3.2 shows the conception diagram of the construction procedure of the superstructure.

Because of the narrow construction yard and the short construction period, many works were done simultaneously in the underground construction. By adopting the Top-Down construction method, the first floor could be used as a construction yard. This method can lead to cut down the construction period significantly. However the Kanae Truss was constructed by conventional construction method because of the extremely demanding high

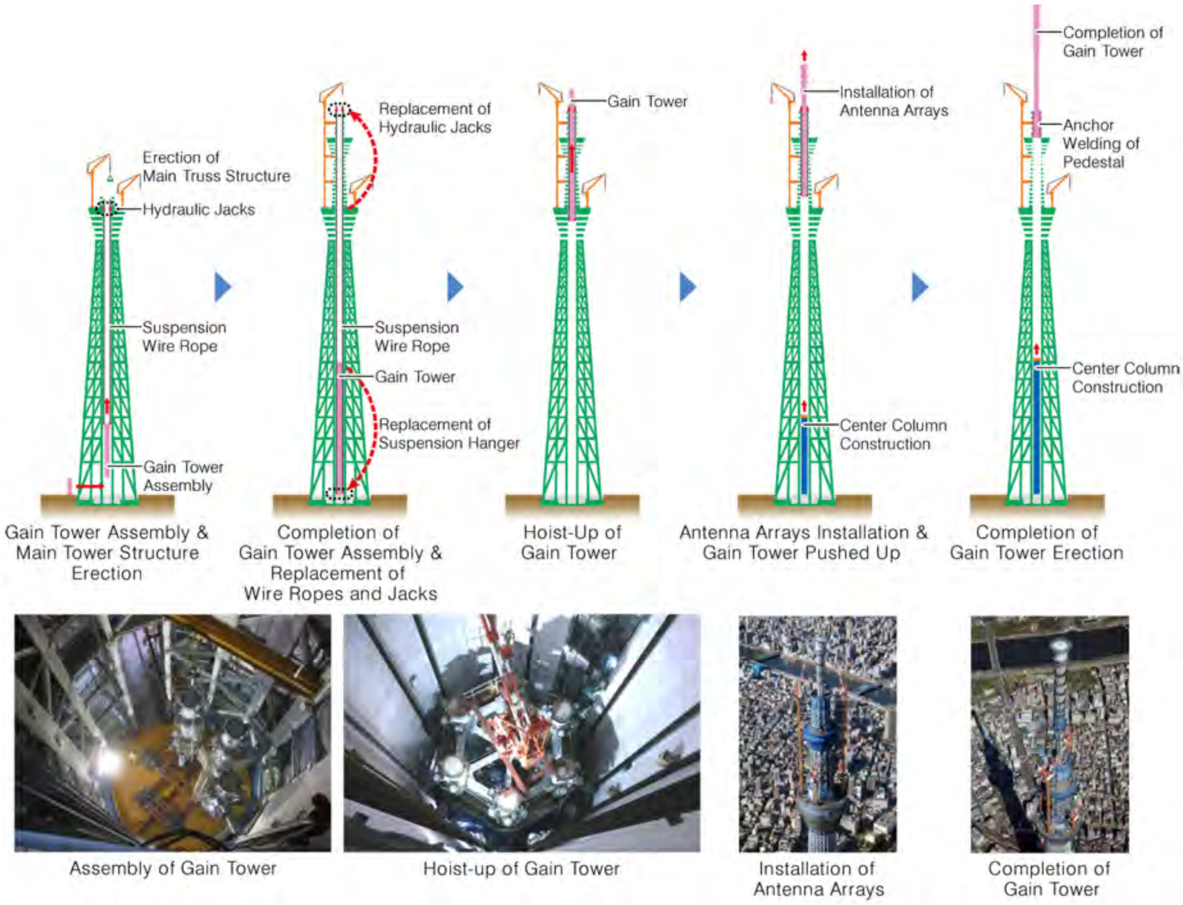

Figure 3.2. Construction procedure.

construction precision for assembling and welding in the field.

The first floor was also used as a space for carrying vehicles and as a construction yard for the foundation works. This floor could make space for the simultaneous work of both the foundation works and the steel frame works. In addition, the fourth floor slab of the lower building was reinforced to be used as a yard for the disposal of heavy goods prepared for the steel works. During construction, steel pipes of the upper tower were placed once on this fourth floor with setting lifting attitude. In the next step, these pipes were lifted up after setting the scaffoldings in place.

3.3. Development of construction method of continuous underground wall pile

3.3.1. Outline of pile works

The continuous underground wall piles in this site are 1.2 m thick at a depth of 35-52 m. The Kanae Piles are composed of 20 panels each and the Podium Piles are composed of 77 panels each. In addition, 131 cast-in-place piles, which are 1.4-2.5 m in diameter and 36-50 m in depth, are set in place.

The continuous underground wall piles were constructed by the OWS-SOLETANCHE construction method. This method has been widely used in 500 million m^2 constructed area in Japan. In the method, first, a consecutive pile hole gets excavated while preventing collapse of the ground by using the stable liquid mainly composed of polymers. Next, the wall pile is built in this pile hole. This wall pile is available to the earth retaining wall, the water cut-off wall, the structural wall, and the foundation pile.

The wall pile with knot was adopted for the Kanae Pile that is a wall-shaped reinforced concrete foundation pile with a knuckle or bumps. Fig. 3.3 shows the diagram of the wall pile with knot (the Knuckle Wall). This was the first time to adopt a steel-framed reinforced concrete construction (SRC structure) wall pile and to use a sand and gravel layer as a bearing stratum, so this method required cautious development.

3.3.2. Procedures of wall pile works

The procedures of continuous underground wall pile works (Fig. 3.4) are following.

1. Excavation work
2. Complete-Water-Stop (CWS) joint work
3. Reinforcing steel bar work
4. Casting concrete work

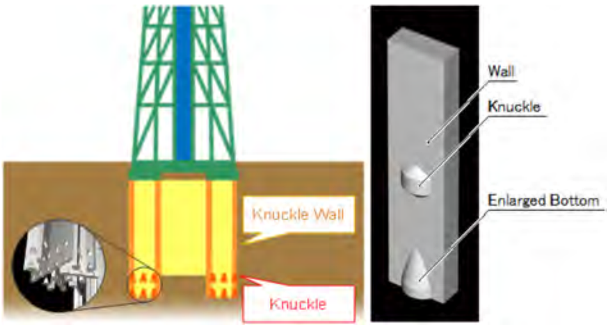

Figure 3.3. Diagram of continuous underground wall pile with knot (the Knuckle Wall).

Figure 3.4. Construction of continuous underground wall pile.

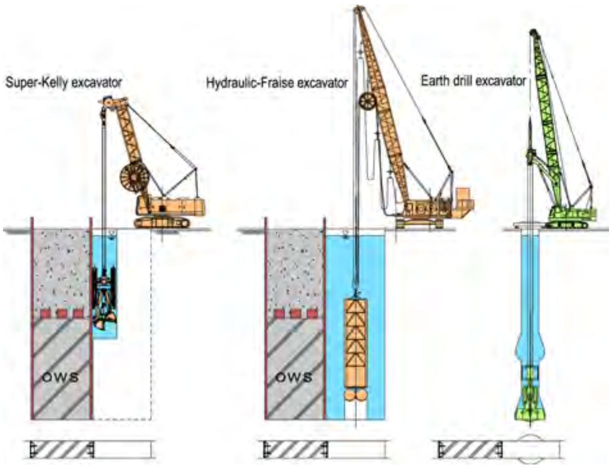

Figure 3.5. Procedure of excavation work.

After excavation and slime treatment of the preceding panel, the corrugated steel with prop support at the end of preceding panel is installed for joint work. A pre-assembled cage of steel and rebar are installed and casted the concrete by tremie pipes. Then panel is cast in concrete and after that the prop support is torn off to expose the corrugated steel. The continuous underground wall pile is completed by constructing these processes repeatedly.

Following are details of those constructions.

3.3.3. Excavation work

The upper soft silt layer was dug by using a grabbing

Figure 3.6. Slime treatment machine for Knuckle.

bucket type excavator machine called Super-Kelly. The lower rigid gravel layer was scraped off by using a Hydraulic-Fraise excavator machine. The knot was made on the outside surface of the wall by using the special excavator. Fig. 3.7 is a Supper-Kelly excavator, and Fig. 3.8 is a Hydraulic-Fraise excavator. After these excavations, slime of the knot was removed by a special treating device. Fig. 3.5 indicates the procedure of the excavation work. Fig. 3.6 shows the slime treatment machine for Knuckles.

The Super-Kelly is highly accurate and efficient, and has a very compact excavator having a bucket hung by wires. Because the grab-shell can transmit a grabbing force efficiently, the Super-Kelly excavator can provide high excavating performance. By checking an automatic inclinometer installed in this excavator, the precision of the excavation can be checked in real time. Moreover, assembling and dismantling of this machine is simple.

The Hydraulic-Fraise excavator, which is a reverse circulation excavator, has high performance cutters to excavate rigid gravel layers. This excavator can be used in many construction sites, such as deep depth and very thick foundation structures. It is also used in extremely narrow sites of construction in dense cities.

By properly using both the Supper-Kelly excavator and Hydraulic-Fraise excavator, these excavators provide highly efficient work and quality foundation walls.

The special excavator for knuckles consists of a steel cylindrical bucket to excavate and a biting device to build knuckles. This biting device sticks out during the excavation by hydraulic power. It carves the stub in the pile hole. A stabilizer is installed in this excavator in order to construct the knuckle accurately. This stabilizer is fixed in the pile hole so as to prevent the vibration of the bucket. Fig. 3.9 shows the expanded excavator for the knot.

3.3.4. Joint work

The CWS(the Complete-Water-Stop) joint was adopted as a joint improved to transmit shearing force by connecting the adjacent foundation wall panels efficiently.

Figure 3.7.
Super-Kelly excavator.

Figure 3.8.
Hydraulic-Fraise excavator.

Figure 3.9. Expanded excavator for Knuckle.

The procedure of CWS joint is as follows: First, corrugated steel with prop support is installed on the inner surface at the end of a preceding panel after excavation, and secondly, this panel is then cast in concrete. Next, after the adjacent following panel is excavated, the prop support is torn off to expose the corrugated steel. Finally, the following panel is cast to form a monolithic construction. This corrugated steel makes structural joints. Fig. 3.10 and 3.11 illustrate these procedures of CWS joint work. Fig. 3.12 shows the CWS joint and the corrugated steel panel.

CWS joint transmits the horizontal shearing force and enhances the horizontal stiffness of the continuous foundation wall.

3.3.5. Reinforcing steel bar work

The foundation walls of the Kanae Piles were constructed by using reinforced-concrete in which the cage of steel frame and bar were embedded, an SRC structure. Fig.

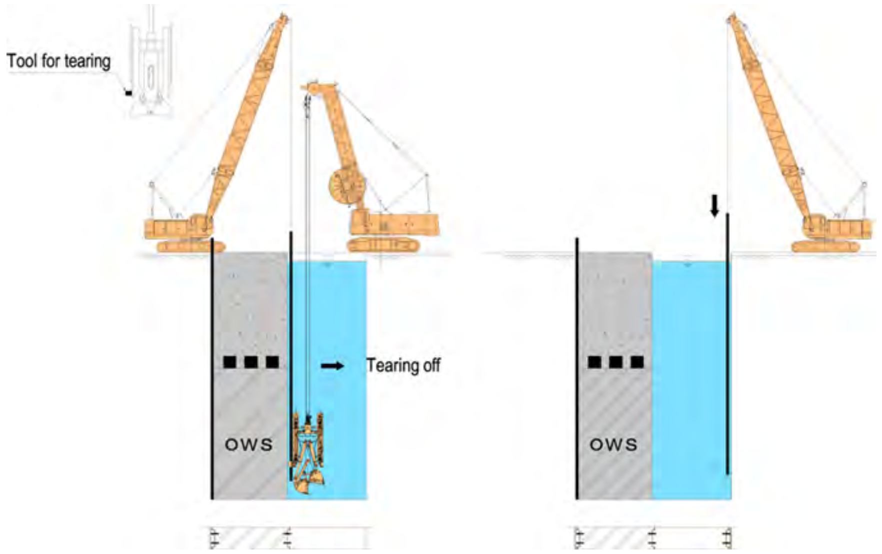

Figure 3.10. Procedure of CWS joint work.

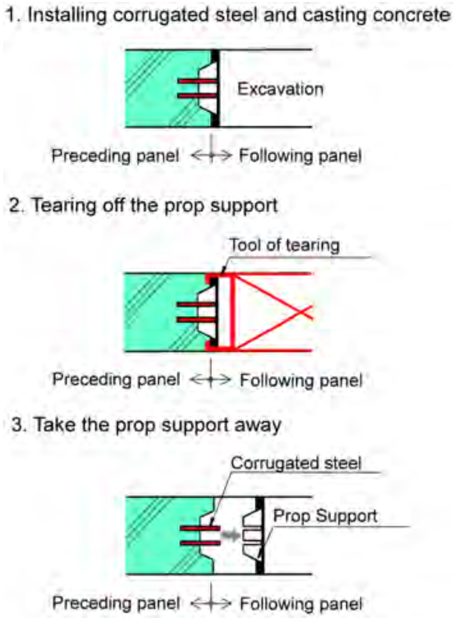

Figure 3.11. Diagram of procedure of CWS joint work.

3.13 shows the cage of steel frame and bar, and Fig. 3.14 shows a section of the SRC continuous underground wall pill.

The cage of steel frame and bar was approximately 40 m in total length. It was assembled in advance on the construction site. Because the weight of this cage might have been too heavy to lift as 50 ton per 1 panel, the cage might have had to be divided and connected at many joints. The construction schedule and efficiency might have been greatly influenced. Therefore, a special construction device was developed to enable the whole cage to stand with only a crawler crane. The efficiency of the construction was greatly improved in regard to shortening of work and cutting down on crawler cranes. Fig. 3.15 is the procedure of the reinforcing steel bar work, and Fig. 3.16 shows the

Figure 3.12. CWS joint and corrugated steel panel.

Figure 3.13. Cage of steel frame and bar.

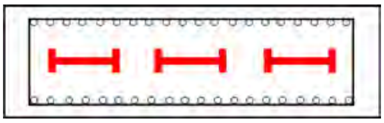

Figure 3.14. Section of SRC continuous wall pile (The Kanae Pile).

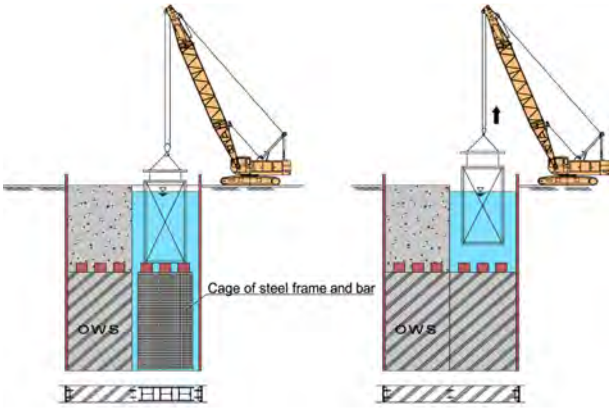

Figure 3.15. Procedure of reinforcing steel bar work.

Figure 3.16. Device to stand the cage of steel frame (left). **Figure 3.17.** Device to have the cage inserted precisely (right).

device to stand the cage of steel frame.

The embedded steel frames in piles had to be constructed with much higher precision, for it would be directly connected to the upper steel frames of the tower. In addition, the embedded steel in the foundation walls was designed to connect to the upper tower steel frame at a position under the working level. From these situations, a new temporary device to insert the cage precisely was developed and made practical. Fig. 3.17 shows the device to have the cage inserted precisely.

This device was designed to allow recycle and reuse. This device led to a shortened period of construction because the embedded steel frames of the foundation walls did not need to be made longer to reach the work level and didn't interfere with the excavation.

3.3.6. Casting concrete work

The cage of steel frame and bar were suspended by wire and gradually brought down till the temporary device held the position 1.0 m above the ground level. Concrete was poured from concrete pump vehicles on temporary stages to cast concrete with four tremie pipes at each panel. Fig. 3.18 indicates the procedure of casting concrete work. Fig. 3.19 shows the setting tremie pipes, and Fig. 3.20 is the view of casting concrete.

3.3.7. Joint between steel in the Kanae Piles and superstructure

The foundation of the Kanae Truss was built by the conventional construction method, because it was necessary to have accurate construction work when connecting the

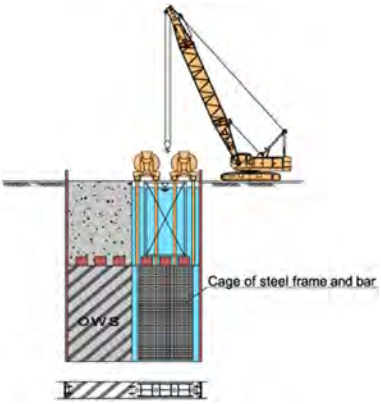

Figure 3.18. Procedure of casting concrete work.

Figure 3.19. Setting tremie pipes.

Figure 3.20. Casting concrete.

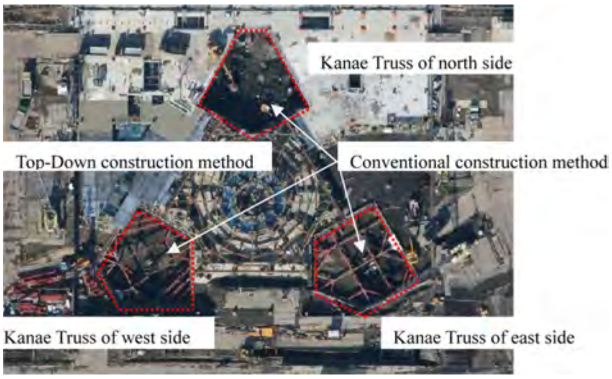

Figure 3.21. Construction of foundation.

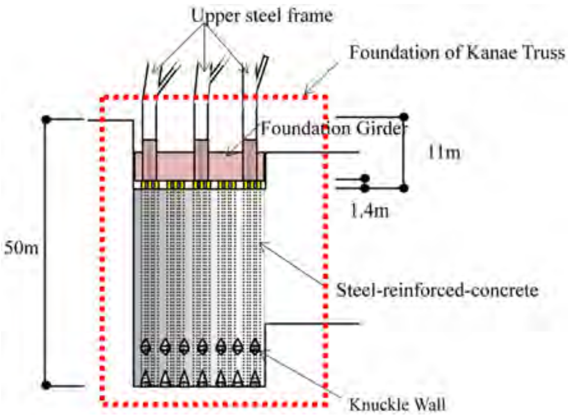

Figure 3.22. Joint between upper steel frame and foundation.

upper steel frame and the embedded steel frame in the foundation wall. The other foundations except for the foundation of the Kanae Truss were built with a Top-Down construction method, so as to provide high efficiency in a narrow construction space. Fig. 3.21 is the view of construction of foundation.

In the foundation built by conventional construction method, the embedded steel frames were exposed about 1.4 m above the bottom of ground that was excavated over GL-11 m. After that, these steel frames in piles had to be connected to the upper-ground steel frame which supported the tower structure. Fig. 3.22 indicates the joint between the upper steel frame and foundation, and Fig. 3.23 shows the foundation steel girder.

4. Conclusion

This paper introduces the outline of the structural design and the construction method of foundation of the TOKYO SKYTREE. This site is the bank of the Sumida and Arakawa rivers. The surface layer of ground is extremely soft and the foundation demanded high performance such as rigidity and strength to bear strong winds and large earthquakes. Therefore, an SRC continuous underground wall pile was developed for this project, and its structural and construction reliability was confirmed with an on-site full scale pull-out test concluding a maximum load of 40000 kN.

Figure 3.23. Foundation steel girder.

References

1. Ministry of Construction, The Building Center of Japan, Hyper-Building Laboratory (2002) The wind force for hyper-building design. Ministry of Land, Infrastructure, Transport and Tourism (MLIT), Tokyo, Japan.
2. MLIT (2007) The Building Standard Law of Japan. MLIT, Tokyo, Japan.
3. Architectural Institute of Japan (AIJ) (2004) Recommendations for Loads on Buildings. AIJ, Tokyo, Japan.
4. AIJ (2004) Guidelines for the Evaluation of Habitability to Building Vibration. AIJ, Tokyo, Japan.
5. Okuma,T. and Tamura,Y (1996) Wind resistant design for building. Kajima-Shuppan, Tokyo, Japan.
6. Konishi, A. (2011) Structural and Wind Resistant Design of Tokyo Sky Tree. CTBUH 2011 World Conference, Souel, Korea.
7. Konishi, A. (2011) Structural Design of Tokyo Sky Tree. IABSE-IASS Symposium, London, England.
8. Konishi, A. (2013). “Wind Resistant Design of Tokyo Skytree.” *Japan Association for Wind Engineering*, 3, pp. 286~291.
9. Konishi, A. (2009). “Wind observation for Wind Resistant Design of Tokyo Sky Tree.” *JWAE*, 3, pp. 349~352
10. Nakai, M. and Konishi, A. (2013). “Performance-Based Wind-Resistant Design for High-Rise Structure in Japan.” *International Journal of High-Rise Buildings*, pp. 271~283.