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Authors: Kenichi Mizutani, Construction Planning Group, Takenaka Corporation
Kiyoaki Hirakawa, Structural Engineering Section, Takenaka Corporation
Masato Nakashima, Building Engineering Group, Takenaka Corporation

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Construction of a 300-Meter Vertical City: Abeno Harukas

Kenichi Mizutani[1,†], Kiyoaki Hirakawa[2], and Masato Nakashima[3]

[1]*Construction Planning Group, Construction Engineering Department, Osaka Main Office, Takenaka Corporation, Osaka 541-0053, Japan*
[2]*Structural Engineering Section, Design Department Osaka Main Office, Takenaka Corporation, Osaka 541-0053, Japan*
[3]*Building Engineering Group, Construction Project Office, Osaka Main Office, Takenaka Corporation, Osaka 541-0053, Japan*

Abstract

Abeno Harukas is the tallest building in Japan and is located in Abeno, which is one of the three main railway transport nodes in Osaka. This building has a height of 300 meters, and its lowest levels are 30 meters below ground. It contains a department store, museum, offices, a hotel, and an observatory. In this urban renewal project, a section of the department store that encloses the station was dismantled and replaced by a supertall building complex, while infrastructure was simultaneously constructed, including: upgrades to the station and the existing department store, improved connections to the subway and pedestrian bridges, and a new pedestrian walkway over the road. In this paper, the ingenious erection processes, newly developed technologies, and precise construction management techniques are introduced for Japan's tallest building.

Keywords: High-rise buildings, Setback structure, Overhanging structure, High-strength CFT column, Outer diaphragm, Sliding cover system

1. Introduction

Abeno Harukas is a highest building in Japan located in Abeno which is one of the three main railway transport nodes in Osaka (Hirakawa et al., 2014). The project site is situated in proximity to the private railway (Kintetsu) line, two subway lines (Midosuji and Tanimachi), tramway line (Hankai) and JR conventional line as shown in Fig. 2. The Osaka Abenobashi Station of the Kintetsu Minami Osaka Line used to be standing on the ground floor of the old department-store building reconstructed in this project. Therefore, construction of this tower required switchovers of passenger circulations while demolishing the old department-store building.

Fig. 3 shows the illustration overview of the following reconstruction steps:

[Owner]	Kintetsu Corporation
[Design and Supervision]	Takenaka Corp. Osaka First Class Architects Office
[Construction]	Takenaka Corp., Okumura Corp., Obayashi Corp., Dai Nippon Construction Co., Ltd., and the Zenitaka Corp. Joint Venture
[Location]	Osaka city
[Zoning]	Commercial District, Fire Zone, Special Urban Renaissance District
[Use Purposes]	Department store, railroad station, office, hotel, Museum, and observatory
[Building Area]	Tower Building: 6,110.00 m^2 (25,000.00 m^2 in total)
[Total Floor Area]	Tower Building: 212,000 m^2 (306,000 m^2 in total)
[Floor Area Ratio]	1,163.73%
[Structural Scale]	Steel (above-ground) + SRC (under-ground) Five basement stories, 60 stories aboveground with one penthouse (legally approved number of stories: 6 basement stories, 62 stories and 1 penthouse)
[Maximum Height]	GL + 300.00 m
[Building Depth]	GL – 30.47 m

Figure 1. Outline of Abeno Harukas.

†Corresponding author: Kenichi Mizutani
Tel: +81-6-6263-5751; Fax: +6-6264-0067
E-mail: mizutani.kenichi@takenaka.co.jp

Figure 2. Project site situation.

STEP-1: Started extension of the Osaka Abenobashi Station's platform to the east in December 2007, and the train stopping position moved closer by 30 meters to the east, prior to demolishing the old building.

STEP-2: Started relocation of a new concourse to the ground floor of the main building in June 2008.

STEP-3: Demolished the old building during the period between March and December, 2009.

STEP-4: Constructed the new tower on the former old building site during the period between January 2010 and around the summer of 2013.

STEP-5: Opened the department store in the tower temporarily in June 2013. Completed the tower in December 2013. Held the grand opening of the whole building in March 2014.

2. Comprehensive Temporary Work Planning

It was required to construct a 300 meter high building right out to the edge of the property, which faces crowded roads in the north, south and west and adjoins the department store open for business in the east. Under the circumstances, it was a critical issue to secure the building materials carry-in/-out routes and construction yards. The construction of some parts of the second and third floors into a later process was brought and thus a space that allowed a free traffic of large vehicles and heavy machines was created in order to solve the above issues. Simultaneously, the construction yard into the structural steel transportation circulation route and excavated earth carry-out yard on the ground floor and the concrete mixer truck parking yard on the first basement floor were separated (Fig. 4).

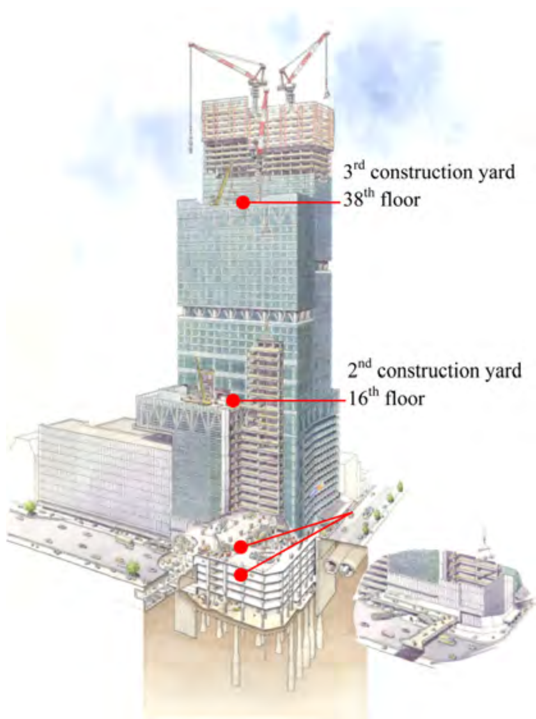

Figure 4. Comprehensive temporary work planning.

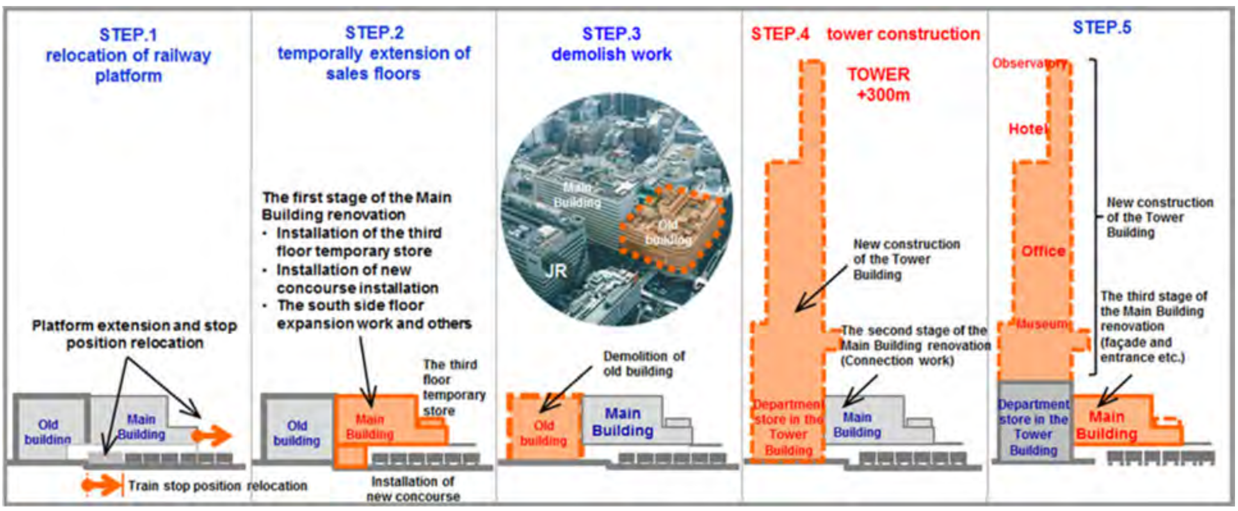

Figure 3. Project reconstruction steps.

Figure 5. Large telpher crane at temporary opening.

During the erection of the office and hotel components, the setback rooftops of the 16th and 38th floor levels were used as the second and third construction yards for such purposes as temporary storage of members for the upper floor levels.

As shown in Fig. 5, a large telpher crane was installed at the temporary opening in the low-rise component and lifted the small steel beams piled up on a large pallet to the upper floors without stopping.

3. Outline of Structural Work

3.1. Construction method for steel structure of special setback shape

3.1.1. Special features of structure

The features of this building's structure are as follows

- The section of the building is set back in steps to the north;
- The hotel component has a 70 meter high void space and a core truss damper inside;
- The structure overhangs up to 25 meters over the rooftop of the adjacent department store;

Our top-priority issue was to ensure the accuracy of the special-shaped steel structure having the above listed features.

3.1.2 Construction issues and resolutions

(1) Prevention of setback structure falling

The construction stage analyses were conducted that reflected the status of the underground framework in each construction step, the temporary opening position on the ground, and the effects of rebound were conducted, and the building behaviors were consequently grasped as shown in Fig. 6.

The building inclination of the office component turned out to be larger than those of the department store and hotel components, which was affected by the hotel component occupying only a half of the office component in the south and the higher axial rigidity of the long columns in the north of the office component. The inclination angles of the spans exceed 1/1000 in some parts. With the hotel component built on it, the relative displacement was approx. 30 mm, compared with the data acquired when the 38th floor was constructed as shown in Fig. 7.

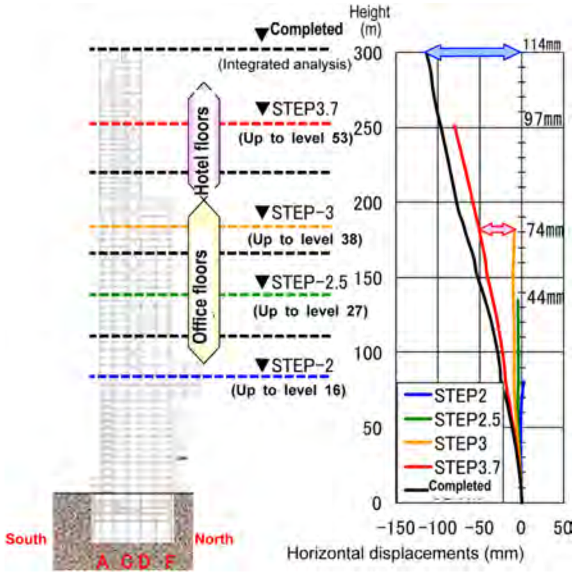

Figure 6. Construction step analysis.

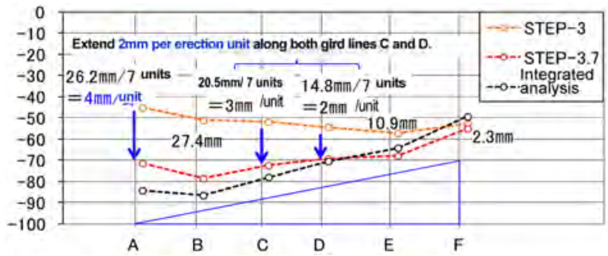

Figure 7. Vertical displacements of 38th floor.

In accordance with the above analytical results, steel columns on the office floors were fabricated so that they extend by 4 mm per erection unit along the southernmost grid line ‘A’ , and by 2 mm per erection unit along the gird lines ‘C’ and ‘D’. The structure was also erected by inclining the building itself by approx. 4 mm per erection unit to the north.

The control method to incline the building to the north by erection units is as follows: It was marked on an upper floor where there was a shift of 4 mm per erection unit to the north from the lower erection unit marking, and that marking on the upper floor was used as standard for control. Then GPS measurements were made almost every three erection units, compared the displacements of inclinations to the north with the absolute coordinates, and proceeded with the work, checking for consistency with the results of the construction stage analyses and thus confirming the validity of the erection plan based on such analyses as well as the overall behaviors.

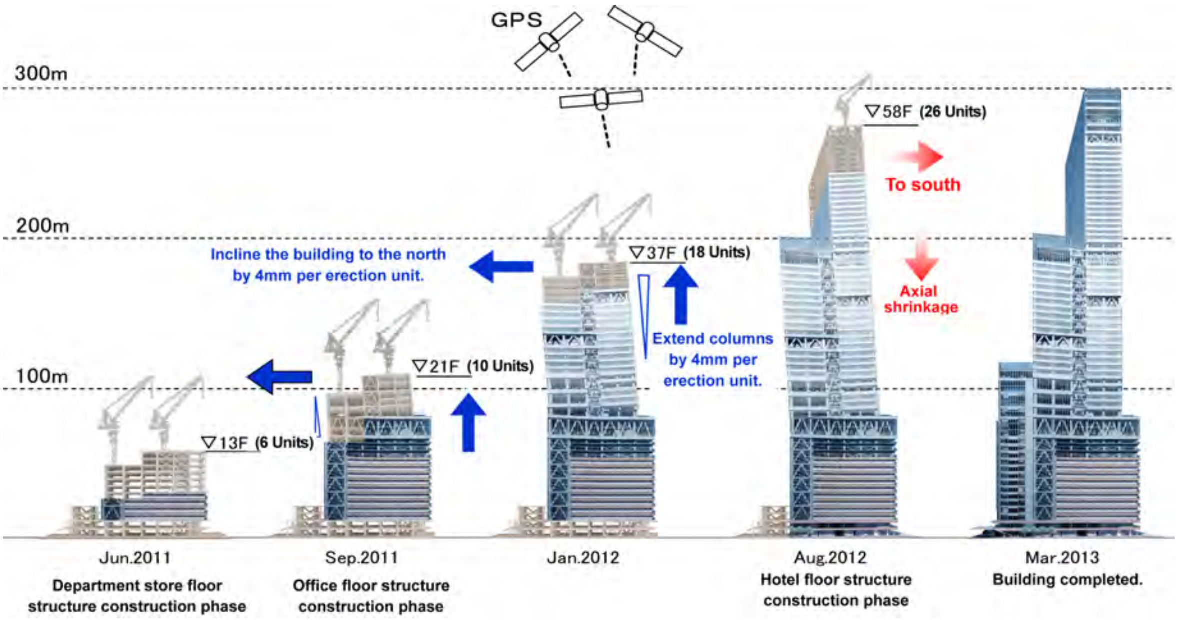

Figure 8. Control method against inclination of the building.

The analytical values and actually measured ones of building inclination were compared, which indicates that the maximum inclination of the building top was 114 mm with the vertical accuracy of 1/2632, which was less than 130 mm, the allowable control value established before commencement as shown in Fig. 8.

(2) Prevention of overhanging structure's deflection

As a method to prevent deflection, overhanging brace members were hung from the main structure side and provided an arch rise, because it was impossible to support the overhanging members (total steel weight was approximately 1,000 tons) by timbering from the roof structure of the main department store building.

It was required in principle to enable the unit members to form a triangle for a truss framework and go to the following step after the final tightening of bolts and welding work. The maximum deflection at the tip of the overhang was 9 mm, which was less than 40 mm, the allowable control value established prior to commencement.

The finishing work of the eaves soffit was commenced immediately after the construction of the overhanging structure with a movable suspended scaffolding for temporary use, which enabled us to proceed efficiently with fire-resistive covering, eaves-soffit backing steel framework, spandrel and other works as shown in Fig. 9.

Figure 9. Suspended scaffolding for finishing.

3.2. Construction techniques for middle and low rise steel structures

3.2.1. Features of middle and low rise steel structures

The noteworthy features of the middle and low rise steel structures of this building are the following:

1) CFT columns using high-strength steel materials;
2) Outer diaphragms in consideration of the concrete self-filling property of CFT columns;
3) Corrugated steel plate wall located in middle-rise component;

The above listed techniques were all newly introduced in this project and confirmed by tests to have sufficient structural performance. However, there was a concern as to whether the structural performance validated in the laboratory could be consistently achieved at the construction site. Various prior verification was tested and employed elaborate methods in the construction phase to remove that concern.

(1) Welding of high-strength and other various steel materials

This building uses 400, 490, 520, 550 and 590 N/mm^2 grade steel materials. The optimum welding materials that

鋼材強度と溶接材料の制限 2010.04.17 技術部

			適用溶接材料		YGW18/19	YGW11/15	
コラム	板・パイプ	神鋼	MG-70	MG-60	MG-56R	MG-50	備考
			MG-S70	MG-S63B	MIX-55R	MIX-50S	
		日鐵	—	YM-60C	YM-55C	YM-26	
			—	YM-60A	YM-55AG	YM-28S	
		現代	—	—	SM-55H	SM-70G	
			—	—	—	SM-70GS	
BCP440	—	690	30kJ／180℃	x	x	x	BCP認定※1
BCP385	SA440	590	—	40kJ／250℃ 30kJ／350℃	x	x	SA[illegible]
BCP325	HT385	550	—	40kJ／350℃	30kJ／250℃	x	JFE認定
—	HT355	520	—	—	30kJ／250℃	x	JIS規定
—	HT325	490	—	—	40kJ／350℃	30kJ／250℃	JIS規定

Figure 10. Quick reference chart for welding.

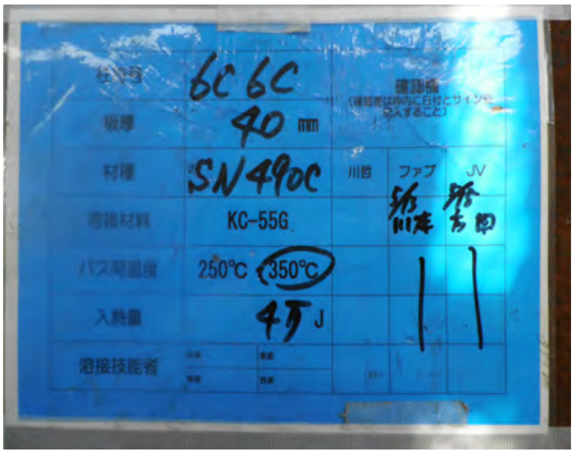

Figure 11. Management chart for welding.

match these various steel panels and the existing columns were chosen and applied. Since their welding heat inputs and interlayer temperatures were different from one another, a quick reference chart (Fig. 10) was prepared for various combinations. The welding workers were carrying copies of the chart at all times and thus prevented misuse. A management chart (Fig. 11) was also posted around each jointing area at the job site to enhance the weld quality.

(2) Welding of outer diaphragms of CFT columns

For the column/beam joints in this building, split-type outer diaphragms are jointed to columns by oblique fillet welding with double bevel groove machining as shown in Fig. 12. A full-scale specimen including outer diaphragms was fabricated in advance in order to eliminate the quality differences among the fabricators/welders, and then macro test specimens from the welded area were taken and the welding skill verification tests were performed. All the building steel product inspectors were also invited from the fabricators/welders and a workshop for them was held for consistency of their viewpoints on the inspection procedures, which contributed to keeping the inspection levels of the fabricators/welders as equal as possible.

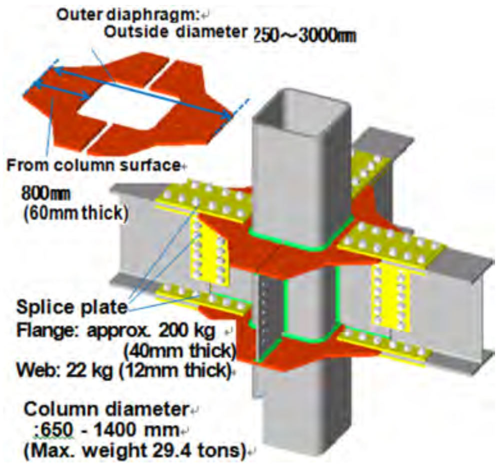

Figure 12. Outer diaphragms of CFT column.

Figure 13. Erection of corrugated steel plate walls.

(3) Corrugated steel plate wall

Corrugated steel plate walls as shown in Fig. 13 are constructed in the middle-rise component of this building to secure the stiffness and strength of the building in the longitudinal direction. The features of this steel plate wall are: (1) It is of corrugated shape; and (2) The installation of stiffened plates orthogonally to the corrugated direction prevents out-of-plane buckling, which consequently can provide a stable plastic deformation performance. A mold that can form a corrugated plate was fabricated easily in order to increase productivity of corrugated steel plate walls. The steel plates are sandwiched in between angles that serve as stiffening ribbed plates to prevent out-of-plane buckling.

3.3. Ultrahigh strength concrete construction

3.3.1. Outline of ultrahigh strength concrete construction

This building uses concrete filled steel tube (CFT) columns made of a combination of high-strength steel mate-

Figure 14. Status of full-scale test.

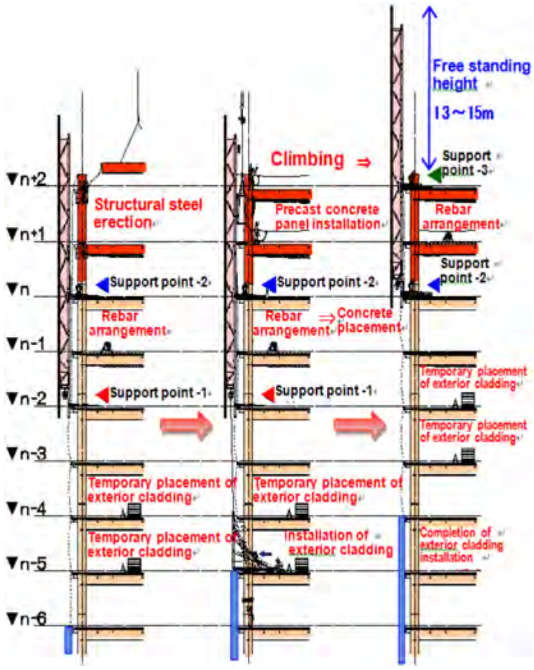

Figure 15. Relationship between slide cover and each floor work.

rials described in the preceding section and ultrahigh strength concrete. The strengths of the ultrahigh strength concrete used here are: 60, 80, 90, 100, 120 and 150 N/mm^2. The last two (with concrete strength (F_c) of 120 and 150 N/mm^2) use silica fume premixed cement for higher strength. Especially for the F_c 150 N/mm^2 concrete, a concrete pump filling test was performed prior to use on the site in order to verify the workability of concrete pump filling.

3.3.2. Workability verification test

The specimens for this test were selected so that the pump filling height and column member dimensions of F_c = 150 N/mm^2 may be the maximum in new building construction projects. The test specimen height was 10.75 meters on the assumption of two stories from the maximum pumping up height of the F_c 150 N/mm^2 concrete, that was, the 20th to 22nd floor levels, and 6 pieces of diaphragms were installed (equal to the quantity of the diaphragms in the assumed areas). The column section dimensions were 1400 mm by 1400 mm by 45 mm (thickness). Full scale tests were conducted as shown in Fig. 14.

3.4. Sliding cover system for construction

3.4.1. Outline of sliding cover system for construction

Hydraulic lifting type protective frames consisting of a very rigid truss (what we call “sliding cover system”) were introduced for this building while constructing it up to a height of 300 meters above the ground for the purpose of protection from falling or scattering materials off the outer periphery of the building. This system enabled the workers to work in a safe environment where the structural steel erection on the top was surrounded with protective framed net fence. Besides, the exterior aluminum curtain walls

Figure 16. Steel erection within sliding cover.

Figure 17. Construction with sliding cover system.

were lifted and installed using a hoist crane mounted below the sliding cover, to reduce the lifting load of the tower crane and thus cut down the construction period (Figs. 15, 16 and 17).

The processes from structural steel erection to concrete placement took place in a space enclosed with the protective framed fence, and the exterior cladding material installation took place on the lower floors. Thus multiple construction processes went on simultaneously and three-dimensionally to increase production efficiency. Simultaneous progress of a wide variety of works in a planar/cross-sectional perspective was rearranged into a three-dimensional perspective, from which a climbing schedule came out without affecting the working time/persons allocated to one unit/floor of each process. Since the critical path for climbing was related to multiple works, various improvements and/or ingenious attempts were applied to each type of work. As a result, 13 day jobs per erection unit (equal to 3 stories) were realized for the structural steel and frame works and 4 day jobs per floor (one team of workers in charge of installing 40 pieces per day) for exterior cladding installation work on the hotel floors at a height of more than 200 meters above the ground. Furthermore, it was successful in two-unit simultaneous climbing (1 meter per min.) and thus increased the number of climbing units per day. A sliding cover system was developed which established a method of preventing construction materials from falling or scattering off the outer periphery of the building which was the most critical issue in construction of this building. Besides, this system has the following three additional advantages:

1) Completing all the structural frame construction works in the area enclosed with this protective frame;
2) Simultaneous use of an exterior cladding installation mechanism;
3) Introduction of a self-climbing mechanism without depending upon a tower crane. These advantages led us to realize nonconventional, rational and safe/secure construction system;

Other features of our safety system included protection roof with a 7.5 meter protrusion which were installed around the scaffolding as safety measures that would help should a material fall off the building during construction as shown in Fig. 18. The steel panels used for the protective shelves were set to 9 mm thick, calculated from the drop impact energy so that even a bolt falling down from a height of 300 meters above the ground may not penetrate through such a shelf panel.

Figure 18. Protection roof.

4. Outline of Underground Work

4.1. Takenaka Soilcement Wall (TSW) construction method

4.1.1. Outline of TSW construction method

Excavating down to as deep as 30 meters below the surface of the ground, surrounded by five conventional railway lines was required. Then, the high-rigidity TSW ("Takenaka Soilcement Wall") Construction Method was used to enable this excavation to a great depth while proceeding with construction in proximity to the structures and rail lines.

The TSW Method uses the same type of excavator as used for the RC continuous wall construction method. This method uses soil cement made of excavated soil the class and particle size of which were adjusted on the ground, instead of concrete, which was placed into the excavated groove through a tremie tube. Soil cement continuous wall was formed, serving as a temporary earth retaining wall and cut-off wall. Since this method recycles the excavated soil, it not only suppresses the generation of construction byproducts but also contributes to reducing the emission of exhaust gases from surplus soil transportation vehicles. Thus the TSW Method is an environmentally-friendly method. For the core of this earth retaining wall, such material as H-shaped steel is inserted as in a soil cement column row wall as shown in Fig. 19.

Moreover, this wall is evaluated as a hybrid basement wall with permanent piles, which consequently reduces the outer peripheral piles, with the aim of rationalizing the construction, reducing the construction period and cutting down the underground obstacle removal and other costs.

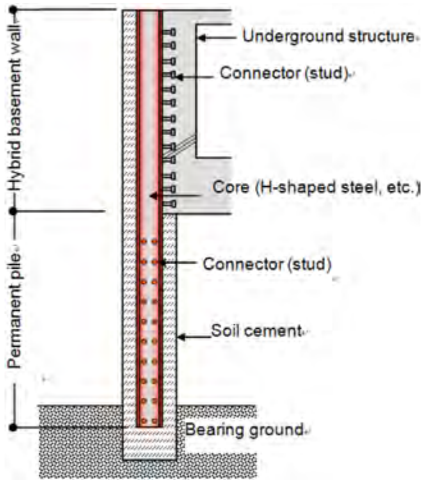

Figure 19. Section of wall with pile.

Outline of TSW Construction Method are as follows:
- Wall thickness; 1100 mm wide 122 units
- Excavation depth; 46~53 meters from the ground
- Core material; H-900×300×16×28 @400-600, 43-53 meters long and 630 pieces
- Retaining construction area; 14,943.7 m^2
- Retaining construction term; 11 months (executed)

The specified design strength of the soil cement of which the earth retaining wall was made, deeper than 30 meters from the ground level, was set to 2 N/mm^2 in this construction method to secure high bearing capacity. A strict mix proportion program was needed to be established to ensure the required quality of soil character that varied according to the progress of excavation.

It was excavated to form an underground continuous wall, produced soil cement by mixing and stirring the excavated soil with cement milk at a plant on the ground (Fig. 20), and placed the soil cement through a tremie tube. As a result, it was possible to reuse approximately 40% of the excavated soil, consequently suppress the generation of construction byproducts and simultaneously reduce the greenhouse gases included in the exhaust gases emitted by surplus soil transportation vehicles. Furthermore, our use of the earth retaining cores as permanent piles led to reduction of the outer peripheral piles and consequent rationalization of construction.

Figure 20. Soil cement plant at site.

4.2. Deep underground *in-situ* concrete piling method

4.2.1. Outline of piling work

The piles to support a 300 meter high skyscraper were in-situ concrete belled piles ("Takenaka TMB Piles") with shaft diameters of 2,300~2,500 mm, expanded bottom diameters of tips that were 3,400~4,200 mm and pile tip level of approximately 73 meters below the ground (Fig. 21). For the underground piled columns, extremely thick materials (up to 90 mm) were used to support high axial forces, and their weights were close to 100 tons. The underground piled columns were approx. 32 meters long due to the deep underground space.

The facts and figures about the piling work of this building are as follows

Total number of piles: 68 pieces
Concrete strength: $F_c = 48$, 60 N/mm^2
Gross excavation amount: 20,055 m^3
(Deepest excavation depth: 70.4 m)
Gross concrete amount: 10,300 m^3
(Up to 340 m^3 per pile)
Gross weight of rebars: 510 tons
(Up to 16.8 tons per pile)
Gross weight of pile head steel pipe: 620 tons

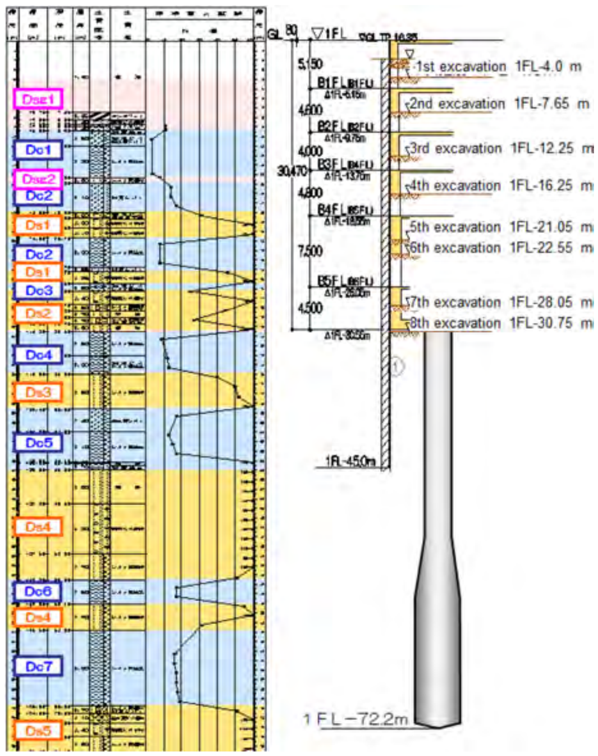

Figure 21. Outline of pile work.

Figure 22. Underground piled column pre-erection method.

(Up to 19.1 tons per pile)
Gross weight of underground piled columns: 2,860 tons
(Up to 98.5 tons per pile)

(1) Underground piled column pre-erection method

The procedure of erecting underground piled columns after erection of steel pipes and reinforcement cages to a given depth involved the risk of causing the underground piled columns to interfere with floating cages and fall the cages down into excavation boreholes (Fig. 22). Therefore, prior verification of the detailing of every pile was conducted. Then, a traverser dedicated for this purpose was developed and the columns were erected by assembling prefabricated components.

The vertical accuracy of underground piled columns in the concrete placement process was measured using a vertical accuracy gauge in alignment with the driving height in the embedment. For the measurement method, the target mounted on the bottom of an underground piled column when fabricated was measured by the vertical accuracy gauge. The vertical accuracy was measured every 300 mm down to the embedment of 1.2 meters and every 500 mm for deeper embedment. The application of this method enabled us to achieve the vertical accuracy of 1/500 in erection of underground piled columns.

(2) Quality control approach in vertical welding construction method

Each underground piled column was split into three components on the basis of the standard that the weight of one component shall be no more than 25 tons (approximately 10 meters long), which were delivered and assembled at the construction site. Generally, there are many cases of using turning rollers that achieve uniform welding quality. However, there was a concern about the risk involved with the erection work of an underground piled column exceeding the height of 30 meters. Moreover, it was difficult to secure a space for welding yard in this project due to the limited site. Under the circumstances, a welding frame was invented by utilizing the permanent pile hole. Since there was a concern that there might be a welding distortion when the accuracy management method was applied, the management value was set to 1/2000 in consideration of accumulated accuracy of the split components. Furthermore, there was thermal expansion due to sunlight during the welding work, which caused a tendency of inclination. The surface temperature control of underground piled columns was added to the measurement items as a countermeasure against that trouble, thereby improving the conventional management approach.

5. Conclusion

This building not only is a skyscraper with a deep underground space but also was extremely difficult to build due to the location and other restrictions. Therefore, a wide variety of construction methods have improved and developed.

The construction commencement took place in December 2007, and the tower building was completed in December 2013. Then the main building celebrated its grand opening in March 2014, in accordance with the reconstruction steps that had been initially planned. Currently, Japan's tallest vertical city is soaring in the land of Abeno, Osaka.

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