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Review Article

A Review of Key Technologies Development of Super High-Rise Building Construction in China

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Super high-rise building is a typical architectural form of urban modernization, and it is also the trend of urban architectural development. This paper reviews the development history of super high-rise buildings in China combined with the engineering practice of representative super high-rise buildings since the 1980s, such as the Shanghai Center, Shanghai Oriental Pearl Tower, Jinmao Tower, Shanghai World Financial Center, Canton Tower, and Shanghai Tower. The development process of the key technologies of super high-rise projects from the aspects of several technologies, such as soft soil pile foundation and foundation pit technology, concrete structure construction technology, integral formwork equipment technology, and steel structure comprehensive installation technology, is also elaborated. At the same time, the Shanghai Tower is selected as a typical case to share the innovative technology of China's tallest building. Finally, prospects for development of super high-rise construction technology are presented.

1. Introduction

As a typical architectural form of urban modernization, super high-rise building can effectively realize the architectural function and value increment, which is the trend of urban architectural development. With the invention of the Otis elevator, the mass production of steel, and the advent of reinforced concrete, the bottleneck technology restricting the construction of high-rise and super high buildings has been gradually overcome, and super high buildings have rapidly developed worldwide. Before the 1980s, the world's high-rise and super high buildings were mainly concentrated in developing countries such as the United States, the United Kingdom, Russia, and Canada. After the 1980s, China gradually moved away from the debate about the construction of high-rise and super high buildings. A large number of high-rise and super high buildings were successively built in large cities such as Shanghai, Beijing, and Guangzhou, among which Shanghai is the most representative. Shanghai's representative ultrahigh buildings and structures are mainly concentrated in Lujiazui of the Pudong New District. Combined with the engineering practice of super high buildings such as Shanghai Center, Shanghai Oriental Pearl Tower, Jinmao Tower, Shanghai World Financial Center, Canton Tower, and Shanghai Tower, etc., this paper analyzes and discusses the development of key technologies for ultrahigh construction projects in China by systematically summarizing and reviewing the development history and key construction technologies of representative super high buildings.

2. Development of Domestic High-Rise Buildings

2.1. Development of Domestic High-Rise Buildings before Liberation. Before the liberation, many of the most influential high-rise buildings were built in Shanghai, China. In 1923, the Shanghai Zilin Xibao Building with a height of 40.2 meters and 10 floors above the ground was built, as China's first high-rise building in the modern sense. In 1929 the

Shanghai Peace Hotel was built, and in 1934 the Shanghai Broadway Building (now the Shanghai Building) was built. In the same year, the Shanghai International Hotel, with a height of 83.8 meters and 22 floors above ground, was built by Fu Ji Construction Factory, becoming China's tallest building in the Far East at that time and maintained its position for 34 years. The Shanghai International Hotel became the zero coordinate point of Shanghai after the liberation, and it is a very famous landmark of high-rise buildings in China [1]. Fu Ji Construction Factory was founded by Tao Guilin (1891–1992) in 1922 and later evolved into the largest construction factory in China. Tao Guilin also became the Chairman of Shanghai and the National Construction Industry Association at that time. The wooden plum blossom piles, steel frames, steam mud brick partition walls, and granite brick walls were used in the Shanghai International Hotel project, of which pile foundation was completed by Kang Yi Yang.

2.2. Development of Domestic High-Rise Buildings after Liberation. After the liberation, the first building in China that surpassed the Shanghai International Hotel was the Guangzhou Hotel built in 1968, with a height of 86.5 meters. Built in 1973, the High Shanghai TV Tower with a height of 210.5 meters became a taller structure than the Shanghai International Hotel. Guangzhou Baiyun Hotel built in 1976 is 120 meters high, which is China's first high-rise building to exceed 100 meters and the first super high building in China. The Shanghai Hotel built in 1981 is 91.5 meters high and is the first building in Shanghai to surpass the Shanghai International Hotel. It can be seen from the development of high-rise buildings during this period that the early urban development after the liberation of China was still at the stage of experience accumulation and development.

2.3. Development of Domestic High-Rise Buildings in the 1980s. In December 1978, China established the policy of reform and opening up. Since then, major cities have been constantly seeking a great leap in development. In the 1980s, Shanghai's high-rise buildings developed rapidly, and Shanghai Construction Engineering completed a number of influential high-rise buildings. Shanghai Center, Shanghai New Jinjiang Hotel, Shanghai Hilton Hotel, Shanghai Garden Hotel, Shanghai Hailun Hotel, etc. were the most famous super high buildings in Shanghai in the 1980s. Among them, Shanghai Center, which was built in 1989, was the largest and tallest super high building in Shanghai at that time. It was built in accordance with international practices introduced by foreign capital after China's reform and opening up. In 1987, Premier Li Peng proposed to promote the "Lubuge Experience" at the National Construction Work Conference of the State Council. Lubuge was a hydropower station project in China at that time. As bidding must be adopted for the loans from the World Bank, China has learned the world's advanced legal practices for construction projects while introducing foreign investment [2]. Shanghai Center was also a construction project that introduced foreign investment at this stage, so project management method was also introduced. It was the first project to adopt the concept of project management in domestic construction projects, which had a profound impact on the field of engineering construction in China at that time. The method has been continuously developed and implemented to this day.

2.4. Construction of Lujiazui during Opening Up and Development of Shanghai Pudong. In April 1990, Shanghai Pudong was developed and opened up, and the Lujiazui area developed rapidly. In the 1980s, Pudong and Puxi in Shanghai, located across the river and facing each other, developed very differently. At this time, there was a saying that "I would rather have a bed in Puxi than a building in Pudong." Before the 1990s, there was no bridge over the Huangpu River in Shanghai, only the Dapu Road tunnel for wars. Pudong was dominated by crowded low-rise residential houses. In the early days of Pudong's development and opening up, people used ferry to get to and from work every day, which is totally different from the current traffic of many bridges and tunnels. This also reflects the tremendous changes in Shanghai's urban construction in more than 30 years of Pudong's development and opening up. The development of ultrahigh buildings in the Lujiazui area of Pudong, Shanghai, represents that of super high buildings in China.

2.5. Development of Domestic High-Rise Buildings in the 1990s. Since the 1990s, Shanghai Construction Engineering has successively undertaken the construction of the tallest buildings and structures in different periods. The construction technology of tall structures has been continuously improved. The comprehensive construction capacity has reached the international advanced level, some of which has even reached the international leading level.

The Shanghai Oriental Pearl Tower, the tallest structure in China in the 1990s, was completed in 1994 and reached a height of 468 meters, becoming the tallest building in China and the third tallest in the world [3]. It was a milestone project in the development of China's structure construction technology. The Shanghai Oriental Pearl Tower Project was very difficult to construct at that time, because before that the tallest building in Shanghai was the 168-meter Shanghai Center, and the construction height exceeded 300 meters, which made it impossible for many technologies to meet the needs of the time. Therefore, at this stage, a large number of new technologies developed by innovation were applied [4]. In 1996, the project of "Research and Application of Construction Technology and Equipment of Shanghai Radio and TV Tower" won the second prize of National Science and Technology Progress Award of China.

The Jinmao Tower, the tallest building in China in the 1990s, is 420.5 meters high. Completed in 1998, it was the first ultrahigh building in China with a height of more than 400 meters [5, 6]. When completed, it was the first tallest building in China and the third tallest in the world. It was also a milestone project in the development of construction technology in China. A hybrid structure system of concrete structure and steel structure was adopted in the project. Such ultrahigh structure system was the first to be adopted in China at that time, and many new technologies were innovatively adopted in the process of engineering construction. In 1999, the project of "Research on Construction Technology of Super High-Rise Buildings-Jinmao Tower 88" won the first prize of National Science and Technology Progress Award of China.

Starting at the beginning of the 21st century and completed in 2008, the Shanghai World Financial Center with a height of 492 meters is the tallest ultrahigh building in China, becoming the tallest building in China at that time and the third tallest building in the world. This project has achieved a breakthrough especially in the scale application of the third generation of polycarboxylic acid system admixtures in concrete [7]. In 2012, the project of "Key Technologies of Shanghai World Financial Center Engineering Construction" won the second prize of National Science and Technology Progress Award of China.

The tallest structure in China is the Canton Tower. It was the first ultrahigh structure in China, with a height of 610 meters. When completed in 2009, it was the tallest tower in the world, but now it is the tallest tower in China and the second tallest in the world [8]. The structure of the Canton Tower Project is complex and changeable. The outer grid is composed of 24 inclined steel-pipe concrete columns with a maximum diameter of 2 meters. The tower is characterized by ultrahigh, torsion, eccentric, air-permeable, and slim-waisted structure [9]. In 2016, the "Key Technologies of Canton Tower Project" won the second prize of National Science and Technology Progress Award of China.

The tallest building in China is the Shanghai Tower, which has a height of 632 meters and was completed in 2015. It is the first super high building in China to exceed 600 meters in height [10–12]. It is now the first tallest building in China and the second tallest in the world. This project has been awarded three-star certification of the highest level of green building in China and the LEED-CS platinum certification of the highest level of green building in the United States. A double-layer curtain wall system is adopted, and a curved building exterior with 120° torsion and 55% upward split is innovatively designed. In 2018, the research achievement of "Key Technology of Shanghai Tower Project" won the Shanghai Science and Technology Progress Special Award of China.

The above-mentioned projects are influential not only in China, but also in the world. Jinmao Tower, Shanghai Tower, and Shanghai World Financial Center, the three tallest buildings in China in different periods in recent times, were awarded "50 Most Influential Tall Buildings in the World in the Past 50 Years" in 2019 issued by the World Society of Tall Buildings. The Shanghai World Financial Center and Shanghai Tower won the academy's annual World's Best Tall Building Award in 2008 and 2016, respectively. Shanghai Oriental Pearl Tower, Jinmao Tower, Shanghai World Financial Center, Canton Tower, and Shanghai Tower are the only five in mainland China. In 2019, they were awarded "The 27 Most Beautiful Skyscrapers in the World" by *Architectural Digest*, a popular American architecture magazine. At the same time, these 5 projects have won the "Zhan Tianyou Award" of the China Civil Engineering Society in the category of science and technology innovation. The Shanghai Tower is the only one in China to be awarded "13 buildings that have redefined the architectural world in the past 5 years" by *Architectural Digest* in 2019 and the International Association of Bridge and Structural Engineering's only Outstanding Structure Award of the Year in architecture in 2016. The Shanghai Tower has also won many other awards at home and abroad, including 2019 Global Innovation Award of International Association of Building Owners and Managers (the first award established and presented by the association in its 112-year history), 2015 Empoli Skyscraper Architecture Award, 2018 China Construction Enterprise Management Association Science and Technology Progress Grand Prize, and 2019 China Architectural Society Science and Technology progress Grand prize, implying its significant influence at home and abroad.

2.6. Comparison of High-Rise Buildings' Development at Home and Abroad. In 1885, a 10-storey home insurance building, the world's first high-rise building of modern significance, was built in Chicago, the United States. 38 years later the 10-storey Zilin Xibao Building, the first modern high-rise building in China, was built in Shanghai in 1923. In 1894, the first 106-meter-high Manhattan Life Insurance Building was built abroad in 1894, and 82 years later, the first 120-meter-high Guangzhou Baiyun Hotel was built in China in 1976. The world's first 400-meter skyscraper was the Empire State Building in New York, USA, built in 1931, with a height of 381 meters. In addition, 67 years later, the Jinmao Tower, China's first 400-meter skyscraper was built in 1998, with a height of 420.5 meters. Compared with the early development of China, the development of high-rise buildings in China lags behind that in foreign countries.

Nowadays, China's high-rise building construction has made a very significant development [1]. At present, there are three super high buildings over 600 meters in the world, with one in China; 10 super high buildings over 500 meters, with 4 in mainland China; 34 super high buildings over 400 meters, with 14 in mainland China; 185 super high buildings over 300 meters in the world, with 85 in mainland China; and 1,688 super high buildings over 200 meters in the world, with 708 in mainland China. From these data, we can see that China's super high buildings have exceeded 40% of the world's total. Now, China has been worthy of being a superpower of super high construction projects, which is attributed to the rapid development of urban construction since China's reform and opening up.

According to Table 1, as of June 2021, six of the world's top ten super high-rise buildings are in mainland China, and according to Table 2, four of the world's ten tallest structures are in China.

3. Soft Soil Pile Foundation and Foundation Pit Project

3.1. Technology of Soft Soil Foundation Pile. Before the liberation, there were a small number of high-rise buildings in Shanghai, and pile foundation of supporting buildings

Table 1: The World's top 20 super high-rise buildings (as of June 2021).

Serial number	Name	City	Height (m)	Floors	Year of completion
1	Burj Khalifa	Dubai	828	163	2010
2	Shanghai Tower	Shanghai	632	128	2015
3	Abraj Al Bait	Mecca	601	120	2012
4	Ping An Finance Center	Shenzhen	599.1	115	2017
5	Lotte World Tower	Seoul	554.5	123	2017
6	Guangzhou Chow Tai Fook Financial Center	Guangzhou	530	111	2016
7	Tianjin Chow Tai Fook Financial Center	Tianjin	530	97	2019
8	CITIC Tower	Beijing	528	109	2018
9	Taipei 101	Taipei	508	101	2004
10	Shanghai World Financial Center	Shanghai	492	101	2008

Table 2: The world's top ten tallest structures (as of June 2021).

Serial number	Name	Height (m)	City	Year of completion
1	Tokyo Skytree	634	Tokyo	2012
2	Canton Tower	610	Guangzhou	2010
3	CN Tower	553.3	Toronto	1976
4	Ostankino Tower	540	Moscow	1967
5	Oriental Pearl TV Tower	468	Shanghai	1994
6	Milad Tower	435	Tehran	2009
7	Kuala Lumpur Tower	420.4	Kuala Lumpur	1996
8	Chimney of Ekibastuz Power Plant	419.7	Ekibastuz	1987
9	Tianjin Radio and Television Tower	415.1	Tianjin	1991
10	Central Radio and Television Tower	410.5	Beijing	1992

usually adopted driven-in wooden piles, with poor ability of wooden piles to control settlement. In the early days after the liberation, with the increase of project scale, pile foundation was mainly on-site precast concrete square piles, and it was highly applied in Shanghai Oriental Pearl Tower. The precast concrete square piles were 48 m in length, with a cross section of 500 × 500 mm. Three-section piles and steel plate were connected, and bearing capacity of pile foundation was designed with 450 t. As construction projects become higher, the load is getting bigger and bigger, and accordingly more requirements are proposed for bearing capacity of pile foundation. However, precast concrete square piles fail to meet the requirements, so the steel-pipe pile technology is developed by Shanghai Jinmao Tower and Shanghai World Financial Center. To be specific, in Shanghai Jinmao Tower Project, steel-pipe piles are used with a diameter of 91.4 cm and pile depth of 83 m. The lengths of the first, second, and third piles are 25 m, 23 m, and 17 m, respectively. When the pile is sent to the ninth layer of silty-fine sand, the design bearing capacity of a single pile reaches 1,500 t [13]. In terms of Shanghai World Financial Center project, steel-pipe piles with a diameter of 70 cm are adopted. The pile depth is 79 m in the middle; at the edge, long and short piles whose depth is 60 m are arranged. The design bearing capacity of a single pile is 750 t. Strictly speaking, steel-pipe piles are suitable for super high-rise buildings with large loads, and quality of construction process can be guaranteed easily [14]. When Shanghai Tower was being constructed, there was Lujiazui area surrounding the construction area, and it had become a dense urban area where construction of high-noise drive-in pile foundation projects was forbidden. Therefore, only concrete bored piles were suitable in soft soil foundations at that time. However, one difficulty was about how to improve bearing capacity of such piles. In order to verify feasibility of concrete bored piles, the researcher conducted a systematic in situ test and researched on the spot. Through technological innovation and process improvement, it was proved that concrete bored piles for soft soil foundations could meet bearing capacity requirements of Shanghai Tower. This project breaks through the tradition of steel-pipe pile technology for soft soil foundations because concrete bored piles are firstly adopted in super high rises above 350 m. The pile length is 86 m, and bottom of piles is sent to the ninth soil layer of silty-fine sand, a typical supporting layer in Shanghai. After piles are formed, the pile-tip grouting process is used to control grouting amount and grouting pressure, improving ultimate bearing capacity of pile foundation by nearly 4 times. The ultimate bearing capacity of pile foundation in test is 2,500 t ~ 3,000 t, and the design bearing capacity of a single pile is 1,000 t. Therefore, Shanghai Tower of 850,000 tons is supported firmly by 955 piles in main building. The bored pile technology applies bentonite mud to protect walls, degritting technology in mud, positive cycle construction technology in shallow soft soil, and back-cycling construction technology in hard strata of deep sand. With respect to verticality control of pile foundation, a complete set of construction technologies are developed innovatively, which improves vertical accuracy of pore-forming by more than 50% compared with the national standard. The innovative construction technology of bored piles has served as a reference for subsequent constructors to apply bored piles in super high-rise buildings on soft foundations in China. According to the research results, concrete bored piles can fully meet construction needs of skyscrapers with super large bearing capacity [15]. The development of soft soil pile foundation technology has laid the foundation for the construction of super high-rise buildings of 800 m and even higher.

3.2. Technology of Soft Soil Foundation Pit. Diaphragm wall is the major form of super large and deep foundation pit projects in soft soil. After long-term development, the construction technology of diaphragm wall has evolved from traditional technology of grabbing soil for grooving into the combination of grabbing and milling to create a groove. At present, the new construction technology of casing milling for grooving has experienced sound development. The diaphragm wall of Shanghai Jinmao Tower is 36 m in depth and 1 m in thickness. It combines technology of grabbing soil for grooving and "two drills and one digging", with the former technology being suitable for soft soils and latter for pan soil, and it is relatively difficult to form a trough in pan soil [16]. The diaphragm wall of Shanghai Tower is 50 m in depth and 1.2 m in thickness. It adopts grabbing soil for grooving and casing milling for grooving in soft soil layer and hardpan, respectively. The grooving in hardpan process is mature, and the construction depth of diaphragm wall has been increased significantly. In addition, casing milling for grooving is practiced in Shanghai Tower Project, which is the first time for Chinese projects to adopt OCJ technology for soft soil foundations. Breakthroughs have been made in construction depth of diaphragm wall [17, 18]. At present, Shanghai soft soil foundation has successfully completed construction verification test of 150 m ultradeep diaphragm wall, and the actual application depth of the project is 105 m, setting a new record for construction depth of domestic construction projects. The casing milling for grooving of diaphragm wall adopts jointless box process, which perfectly solves possible turbulence control problem caused by concrete pouring of the ultradeep diaphragm wall and abandons the technical bottleneck that traditional joint box is easy to pull off in construction of ultradeep diaphragm wall.

In soft soil foundation projects in Shanghai, with continuous expansion of scale of super high-rise building foundation pits, it is common to see foundation pits with a single-story area of over 20,000 m^2 and a depth of more than 20 m. It is difficult for the traditional construction methods such as single normal construction method and single reversed construction method to meet the optimal control goals of construction period, cost, and environmental protection. Therefore, combination of foundation pit support technologies is popular [19]. In particular, projects where foundation pit divisions are separated apply combination of normal construction method, and combination of normal construction method and reversed construction method. If there is no separation, the combination of normal construction method and reversed construction method, and the combination of reversed construction method for beams and normal construction method for slab develop fast as foundation pit support technologies. A large number of projects have become classic cases of foundation pit construction in soft soil.

Here is the case of construction of foundation pit of Shanghai Jinmao Tower. Support technology of combining normal construction method is adopted in separated zones of foundation pit. The single-layer area of the foundation pit is 20,000 m^2, and the depth is 19.65 m. Due to control of dominated construction period of main building, support method by zones is adopted in the main building and the podium, which means the main building will be constructed first, followed by podium. The construction of foundation pit abandoned traditional construction concept at that time. The support system was designed as an integral of excavator platform, parking platform, and vehicle trestle in the construction process, dramatically improving construction efficiency and ensuring safe construction of foundation pit. This is an innovation and is widely adopted in the subsequent construction of deep and large foundation pits.

In construction project of foundation pit of Shanghai Tower, the support technology combining normal construction method and reversed construction method suitable for division is applied. The single-layer area of foundation pit is 30,000 m^2, and the depth is 33.1 m. In main building area, normal construction method applicable to partition of circular diaphragm wall enclosure is adopted, and partitioned reversed construction method is used in podiums [20]. At the same time, there is a 121 m large-diameter circular self-standing diaphragm wall enclosure structure in main building area, and it is constructed firstly, aiming to minimize construction period of the main building to the largest extent. This is the self-standing enclosure structure with the largest diameter on soft soil foundation, but construction difficulty is how to guarantee roundness of self-standing circular support structure. The control of roundness is the key to success or failure. In podium area, replacement of floor slab with support is another reversed construction method, which can greatly save project cost provided that construction period is not dominated. In successive construction process of the floor slab around the podium, basin-type earth excavation construction method of "cross" slab symmetry first is used, to effectively control deformation of the surrounding environment of the foundation pit [21].

For example, Shanghai Xinzhuang Longzhimeng Foundation Pit Project adopted reversed construction method and normal construction method in the pit zone without partition walls. The single-layer area of foundation pit is 27,000 m^2, and the depth is 20 m. The main method is reversed construction method of stepping ring plate structure at the side of foundation pit, but in middle structure, normal construction method is applied according to partitions. Furthermore, an oblique ramp for earth-moving vehicles to enter foundation pit is set in light of ring plate structure, so as to meet highly efficient earth excavation. Another example is foundation pit of Shanghai Lujiazui Financial Center Building, where the technical method of replacing temporary supports with structural beams is introduced. The main process is that reversed construction method is resorted to for replacing supports with frame beams. Besides, frame superimposed slab structure is constructed in accordance with normal construction method, and so is the main building area.

With the progress of foundation pit project construction technology, micro-deformation control of environment has become a new difficulty in controlling foundation pit. The construction of deep and large foundation pits in central urban area not only aims to meet needs of construction main basement, but also is particularly important for deformation control of adjacent underground lifelines and ground protection buildings. Deformation control of adjacent protection objects is a new research perspective of foundation pit projects. In recent years, Shanghai Construction Group (SCG), Tongji Architectural Design, and other companies have conducted extensive research and project practices related to the micro-deformation control technology of construction environment of deep and large foundation pits. In terms of the technical problem that environmental disturbance control around enclosure cannot be solved by reducing deformation of the enclosure, an analysis method that helps explore depth of impact of unloading rebound in soft soil foundation pit and the displacement field of deep slip band bypassing bottom of enclosure is proposed. Influence mechanism of environmental disturbance around large and small foundation pits was revealed. Divisional support and divisional unloading enclosure of the foundation pit and its micro-deformation control technologies of surrounding environment were established, which provides technical methods for design and construction of foundation pit with strict micro-deformation control in the soft soil area of Shanghai. Based on deformation control mechanism of deep slip band, design technologies are established for small partitions of super large foundation pit far away from the protection objects and short divisions of super long foundation pit close to the protection objects. For the construction of large foundation pit at the far end of protection objects, a symmetrical, balanced, and block-time-limited excavation mode for the deformation control of the soft soil rheological properties is constructed. As for construction of narrow and small foundation pit near the protection objects, deformation of foundation pit is intelligently controlled through coordinated use of steel support axial force servo system. Various micro-deformation control technologies can be applied comprehensively to control deformation of protection objects at millimeter level. Technical methods for deformation control of foundation pit earth excavation enclosure on rheological properties of soft soil could be found in Chapter 23, Construction of Foundation Pit Earthwork, in Handbook of Foundation Pit Project [22]. The micro-deformation control technology methods of foundation pit projects are listed in Technical Standard for Micro-Deformation Control of Foundation Pit Project (Shanghai Standard) edited by Shanghai Construction Group (SCG) and Tongji Architectural Design. The standard is the first standard in China that boasts of super level quantitative control indicators and explains micro-deformation control in design and construction of foundation pit [23].

4. Concrete Construction Technology

4.1. Concrete Construction Technology in the 1980s. In the 1980s, self-mixing concrete has been adopted in most concrete projects. In 1980, the Japanese equipment was introduced in the Shanghai Baosteel Project, and the construction technology of commercial concrete with wood calcium admixtures and fly ash was developed. The 7,100 m^3 large-volume foundation slab pouring has been completed at Baosteel Project by Shanghai Construction Group. Since then, the research on crack control technology for mass concrete pouring has been carried out. In 1985, the number 300 and number 350 strength grade concrete have been fully adopted in Shanghai Center. The total volume of the foundation mass concrete reached 5,500 m^3, and the thickness reached 2.25 meters. In order to solve the problem of concrete crack control, a layered pouring method was adopted. The first layer of concrete was poured. The thickness is 1.2 meters. The second layer of concrete is constructed after the curing is completed. The thickness of the second layer of concrete is 1.05 meters. The layered pouring to reduce the volume becomes a method of concrete crack control. In 1986, in the Shanghai Hailun Hotel project built by Shanghai Construction Engineering, the foundation concrete number was 300, and the concrete volume reached 8,700 m^3. During the process of construction, the concrete was poured at one time, and the mass concrete cracks were controlled at one time, setting a new domestic record. The concrete transportation height of the Shanghai Center physical structure reached 168 meters at one time, setting a new domestic height record for the performance control of the concrete transportation at one time [1].

4.2. Concrete Construction Technology in the 1990s. In the 1990s, the second-generation naphthalene-based admixture single-mixed fly ash concrete construction technology was mainly developed. The Shanghai Oriental Pearl TV Tower has been under construction since 1990. The number 400 strength grade concrete was adopted, and the maximum pumping height of the solid structure concrete was 350 meters at one time. The Jinmao Tower Project construction started in 1994, and C50 and C60 strength grade concrete were used, of which the construction technology reached a higher level. The base slab concrete of the main building of Jinmao Tower is 4 meters thick with a square volume of 13,500 m^3. The C50R56 strength grade and age-required concrete has been adopted. The positive and negative circulation balanced cooling water pipe cooling system became an effective method for mass concrete temperature control within 100°C. Furthermore, the highest internal temperature rise of the Jinmao Tower base concrete was 96°C. The maximum C40 strength grade concrete pumping height at one time for Jinmao Tower Project solid structure reached 382.5 meters, which created a new domestic and foreign record of the maximum pumping height of the solid structure concrete at one time [24].

4.3. Concrete Construction Technology since the 21st Century. In 2005, the third-generation polycarboxylate-based admixture with fly ash and slag double-mixing concrete construction technology have been fully adopted in the Shanghai World Financial Center, with C50 and C60 strength grade concrete. Self-compacting concrete succeeded in scale application for the first time in super high-rise buildings, and concrete performance indicators have been comprehensively improved. The bottom plate concrete of the main building of Shanghai World Financial Center is 4.5 meters thick, with a square volume of 28,900 m^3. C40R60 strength grade and age-required concrete was adopted. Due to the double-mixing concrete technology, cement consumption was substantially decreased. The temperature rise of the concrete is controlled without the need for water pipe cooling system. The maximum temperature rising inside the mass concrete pouring is only 68°C, which created a new record for the control of cracks for the one-time continuous pouring of large-volume concrete in domestic and foreign construction projects at that time [7, 25]. The maximum C60 and C40 strength grade concrete pumping height at one time for solid structure reached 290 and 492 meters, respectively, which have created a new domestic record. In 2010, the foundation slab concrete of the main building of the Shanghai Tower was 6 meters thick and 121 meters long, with a total volume of 60,000 m^3, using C50R90 strength grade and age-required concrete, with the internal temperature rise of the concrete is up to 71°C [26]. High performance mineral admixtures and high efficiency admixture were used together to reduce the hydration heat, which reduced the cracking risk of mass concrete in the project of the Shanghai Tower. In 2014, the one-time pumping height of C35 strength grade concrete in the Shanghai Tower Project was 607.8 meters, and 120 MPa concrete was pumped to the height of 620 meters at one time as a proof experiment. The Shanghai Tower has created a new record at home and abroad for the control of cracks in one-time continuous pouring of mass concrete in construction projects [27]. It has created a new record at home and abroad for the pumping height at one time for solid structure, surpassing the 601-meter height record of the world's tallest building, Burj Khalifa [28, 29].

A breakthrough has been made in the crack control technology of large-volume, high-strength, low-hydration-heat, and low-shrinkage concrete, and the control of the one-time pumping height and performance control of concrete has also continuously broken new records. The unit cement consumption of concrete can be reduced by more than 50%, the adiabatic temperature rising can be reduced by above 12°C, the 180-day shrinkage value of concrete can be reduced by more than 50%, and the comprehensive application of new technologies can reduce the conveying resistance by more than 50%. Judging from these index data, concrete construction technology has been achieved with all-round development [30].

4.4. Concrete Construction Technology System. In recent years, Shanghai Construction Group has made remarkable achievements not only in concrete engineering practice but also in theoretical research. In terms of mass concrete construction, the law of temperature difference evolution during concrete construction process was revealed, and temperature control technology based on temperature gradient concept was established on research and engineering practice. In super high conveying concrete construction, a discrete element analysis of coordinated control of comprehensive performance indicators and the control technology of rheological parameters were established. In the aspect of vertical deformation control of super high-rise construction, the technology of vertical deformation modeling analysis, process evaluation, and construction control of super high-rise structure have been established, and the elevation classification of different sections of super high structure construction with compensation precontrol method has been established. The development of concrete construction technology for more than 20 years has been summarized. The cast-in-place structural engineering and the corresponding acceptance content have been adopted by the national standard system. On the basis of technical research and engineering practice, the provisions of the construction control technical methods for concrete pouring of different structures have been formulated, which are included in the "Cast-In-Situ Concrete" chapter of the newly compiled national standard "Construction Specification for Concrete Structures," GB50666-2011 [31]. Quality control has been formulated and revised in standard provisions. For example, the verticality control standard for super high-rise buildings is included in the revised national standard "Quality Acceptance Specification for Concrete Structure Engineering Construction", GB50204-2015, "Cast Structure" chapter; a new national standard provision system for "Cast Part" has been established [32].

5. Integral Formwork Equipment Technology

5.1. Development History of Integral Formwork Technology. Integral formwork equipment has now become very important equipment for China's super high-rise construction. In 1992, the Oriental Pearl TV Tower has pioneered the use of the integral steel platform formwork technology based on the inner tube and outer frame technology. Then, the integral steel platform formwork technology based on the temporary steel column technology, the rigid steel column technology, the steel beam tube frame technology, and the steel column tube frame technology have been invented in the construction of major projects, of which five different types of integral formwork equipment technologies have laid the foundation for the construction of China's ultrahigh engineering. In recent years, these technology systems have been adopted in the tallest buildings and tallest structures in different periods in China [33].

5.2. Development of Traditional Integral Formwork Technology. Aiming at solving the technical problems of traditional climbing formwork process bearing capacity, three-dimensional protection, and construction efficiency, the integral formwork technology of inner cylinder and outer frame supporting climbing was created in 1992, forming an integral mobile fully enclosed safety protection operation system. The technology has been applied to the Shanghai Oriental Pearl TV Tower Project for the first time. In 1996, the integral formwork technology of temporary steel column support for climbing, innovative wall top bearing method, support and climbing system integration technology were invented, which solved the problem of heavy-load and large-span construction. The integral formwork equipment technology of temporary steel column was applied in the Jinmao Tower and the World Financial Center Project [34, 35]. As to the Canton Tower Project, since 14 steel stiffened steel columns were set in the concrete core wall, the stiff steel columns have been used instead of temporary steel columns as supporting climbing tools. The integral formwork technology of rigid steel column support for climbing has been innovatively formed [36]. After 2007, the overall formwork equipment technology method has been adopted in a large number of projects including Guangzhou West Tower and Guangzhou East Tower. So far, the overall formwork technology concept has been widely adopted in the industry.

5.3. Development of Integral Formwork with Intelligent Control Technology. The traditional monolithic steel platform formwork technology solves the technical problems of low bearing capacity of the frame, low construction efficiency, and imperfect three-dimensional safety protection, but technical problems such as the diversified power drive, standard modular integration, intelligent operation control, and special structural layer adaptation have not been solved yet. The national "Twelfth Five-Year" science and technology support plan project undertaken by Shanghai Construction Group "Research and Demonstration of Formwork and Transfer Pump Equipment for Thousand-Meter Super High-Rise Construction of Integrated Steel Platforms" (2014BAJ03B00) and the national "Thirteenth Five-Year" key research and development plan project "Development of Key Technologies for Integrated Platform and Equipment for Industrialized Construction On-Site" (2018YFC0705800) carried out system research and engineering practice, and the integral formwork equipment technology with intelligent control has been developed. Aiming at solving the technical problem of the high-quality development of the integral formwork equipment, the intelligent controlling integral formwork equipment technology with bottom-mounted jacking type and the intelligent controlling integral formwork equipment technology with upper-mounted lifting type were invented. The hydraulic power system can be set at the lower part or the upper part of the steel platform according to the engineering needs, and the adaptability of special structure construction is significantly improved, of which two intelligent controlling construction methods have become a new type of integral formwork equipment technology with intelligent control [37, 38].

In terms of intelligent control and standardized design, the new integral formwork equipment technology realizes the intelligent control of the whole process of climbing operations, and the construction of the digital standard modular series product library has been completed. The equipment turnover rate can reach more than 90%, and the industrialized construction technology of modular integration has been fully embodied. The digital design and virtual simulation construction has been realized through the developed platform system. The on-site construction process could be digitally and intelligently controlled [39].

In view of the difficulty of the construction of the integral steel platform formwork in the special structure layer, the hydraulic power drive control of the scaffold integral displacement technology was developed to solve the construction problems of the structure splitting and the body shape conversion. The rigid steel plate with the double-layer operation mode was developed, and the construction problem of the shear steel plate layer installation has been solved by the fixed-point in-place sliding installation technology. The installation technology of the flexible deformation conversion of the steel platform and the scaffold has been developed to solve the construction problem of the outrigger truss layer. The new integral formwork equipment technology has changed the construction difficulty of the special structure layer of the traditional integral formwork system, so the construction efficiency is greatly improved, and the construction risk is greatly reduced [40, 41].

The integration of integral steel platform formwork equipment and construction machinery is also a fast-developing technical aspect. In order to reduce the intensity of construction work, improve the level of integrated construction technology, and solve the problem of large-scale construction machinery attaching to the structure and the efficiency of climbing construction work, integrated formwork equipment with hoisting tower cranes, passenger and cargo elevators, and concrete placing machines technology has been developed and established. The integration of the integral steel platform formwork equipment and the hoisting tower crane is relatively complicated. The developed integrated connection control device can realize the efficient separation and switching between each other, and the efficient climbing and operating of the integral formwork equipment attached to the hoisting tower crane have been completed. The use of the non-bolting, non-welding high efficiency contact support technology; the traditional connection method of the lifting tower crane; and the main structure has been completely abandoned, greatly improving the construction efficiency. The integration of the integral steel platform formwork equipment and the people-cargo elevator is mainly realized by the way of sliding connection attached to the wall without separation from each other, which solves the technical problem of the people-cargo elevator directly rising to the top of the overall steel platform for efficient transportation [42]. The main method for the integration of the integral steel platform formwork equipment and the concrete spreader is to set the concrete spreader directly on the top of the integral steel platform, and it is realized by a fixed method of efficient assembly and disassembly connection or a track-type connection method. The integrated technology application of integral formwork equipment and mechanical equipment with a load of more than 2,000 t has formed a new efficient construction mode.

5.4. Theoretical Basis and Standard System. The theoretical basis and standard system of the integral formwork equipment structure analysis, design calculations, construction methods, and construction control have been established based on engineering practice, experimental research, and theoretical research. The hysteresis test research is mainly carried out for the key components and nodes of the integral formwork, and the design is optimized through experiments to provide a basis for the selection of the calculation model parameters. The wind tunnel test provided evidence for the formulation of the wind load design value and the construction control limit of the integral formwork equipment [43]. Summarizing the development achievements of integral formwork equipment technology in more than 30 years, the first national integral formwork industry standard "Integral Climbing Steel Platform Formwork Technical Standards", JGJ459-2019, has been edited [44]; the terminology system has been unified; the structural analysis has been established; and the design calculation standards, standardized structural requirements, and work safety regulations have been formulated. The first published book "Ultrahigh Structure Construction of Integral Steel Platform Formwork Equipment Technology" systematically discussed the integral formwork technology, established the theoretical basis of the integral formwork, constructed the integral formwork technology system, and discussed the engineering application methods in detail. The industrialized application of the established major equipment has laid the foundation. The major equipment technology of the integral formwork won the second prize of the National Technical Invention of China. The integral formwork technology has been industrialized in hundreds of projects in more than 20 cities. The integral formwork technology of the Jinmao Tower Project has created the speed of building a one-story structure in China in two days. The overall turnover rate of the integral formwork equipment that can actually be achieved is more than 90%.

6. Comprehensive Installation Technology of Steel Structure

6.1. Installation Technology of Mast Integral Lifting. A mast is usually set on the top of a super high TV tower project, and the installation of the mast is also a key technology for the construction of a super high structure. The mast of Shanghai Oriental Pearl TV Tower weighs 450 t, and the mast height is 118 meters. The integral lifting technology of steel strand is adopted without counterweight hydraulic jack. The space is reserved in the middle of the tower, and the mast is transported to the bottom of the tower for connection. Lifting installation was done after the connection was formed as a whole, and the top mast was connected to the top of the tower structure after being out of the barrel [45]. The total height of the mast of the Canton Tower Project is 150 meters, the height of the lifting section is 90 meters, and the lifting section weighs 630 tons. The integral lifting technology of steel strands without counterweight hydraulic jacks is also used. The mast part outside the lifting section is hoisted. The tower crane is installed and connected in sections, and then the mast part that has been installed first is used as the cylinder to set the jack steel strands. The lifting section is connected in sections by the tower crane to form a whole, and finally the whole is lifted and installed in place [46]. For the connection between the mast and structure of the Canton Tower Project, a detachable anchoring method is adopted, which is convenient for the height reduction of the mast during use. The height of the Canton Tower mast was initially 610 meters, and after completion, it was lowered by 10 meters according to relevant requirements. Now, the current height of the Canton Tower is 600 meters.

6.2. Installation Technology of Complex Steel Structure. In terms of super high-rise buildings, Jinmao Tower is the first building in China to exceed 400 meters in height. In response to the problems of compression deformation, shrinkage and creep of super high steel-concrete structures, and vertical deformation and control of stack drop, the precontrol method of elevation compensation in different section has been adopted. The set of technical methods for controlling floor elevation is the first to be developed and applied in engineering practice in China.

The main member bars of the outer steel frame project in the main structure of Jinmao Tower are connected by bolts, and the main connection nodes are connected by pin shafts. The accuracy control requirement is within 2 mm. The rigid steel structure of the giant column is processed in sections. The steel structure of the giant column is hoisted first, and then the frame beam structure is hoisted. The outrigger truss is preassembled in the factory. Then, it is hoisted on site. The outrigger truss is first articulated and connected in the structure construction. After the top is deformed and stabilized, the final fixed connection is carried out. The total weight of the spire is 40.7 t, and the total length is 50.4 meters. The technical method of double tower crane has been adopted when it is installed. The steel structure installation project of Jinmao Tower has become a typical project of full bolt connection [47].

The main member bars of the outer steel frame project in the main structure of the Shanghai World Financial Center are all connected by welding, and the steel structure system of giant columns, giant diagonal braces, ribbon trusses, composite floor slabs, and outrigger truss has been further developed [1]. The outer steel frame part was hoisted in advance with the huge four-corner rigidity column. A stable steel structure system with the four-corner rigidity has been formed by the connection between the floor frame beam and the core tube, and then the four-corner large rigidity and stable steel structure were used to extend to each side to continue installing the frame beam steel structure. Horizontal beams and columns on each level are used in the giant diagonal brace for stable installation and connection. The form of local articulation has been adopted in the installation of outrigger truss, and the welded final connection is carried out after the deformation is stable on both sides. The steel structure installation project of Shanghai World Financial Center has become a classic project of all-welded connection.

The structural system of the outer steel frame project in the main structure of the Canton Tower is very complicated, and its super high, eccentric, torsion, slim-waisted, air-permeable, and flexible structural features make installation difficult. As the steel structure is a large eccentric 10 m structural system, the integrated method of construction monitoring control, operation, and maintenance sharing has been adopted in the installation and displacement control of steel structure, which realizes high-precision installation of steel structure. In order to solve the deformation control problem of the key connection nodes of the steel structure, an in-line radial joint bearing universal hinge adapted to the torsional deformation of the outer cylinder steel structure was innovatively developed to achieve the coordination of in-plane deformation and torsional deformation. The universal hinge connection method is the first successfully applied one. The design method of staggered and obliquely crossed outer tube nodes has been adopted in the key connection node of the steel structure, which fully reflects the visual aesthetic effect of the building. In response to the predeformation control problem, a new structural predeformation control technology of segment adjustment and ring-by-ring resetting was developed to form the segment outer frame steel structure column, diagonal brace plane, ring beam predeformation, and stage vertical predeformation control technology. In order to solve the problem of safety protection for suspended operations, a safety protection system integrating satellite operating platforms, radial channels, and multiple isolations for suspended operations has been developed to achieve efficient and safe construction [46].

The Shanghai Tower is designed with a double-skin glass curtain wall system, and an integrated structural system of internal rigidity and external flexibility has been adopted in the structure. The internal structural system is similar to the traditional steel-concrete structure [10]. A flexible suspension structural system has been adopted in the external structural system, and the external flexible suspension structure is connected to the internal rigid structural system. 4 M1280D tower cranes have been adopted in the installation of steel structure. In order to improve the ergonomics, the weight of the steel structure section unit is controlled within 100 tons, and 2 M1280D tower cranes are adopted in the super large components for dual crane installation. The difficulty in the steel structure engineering of the Shanghai Tower lies in the precontrol installation technology for the deformation of the outer flexible steel structure. How to solve the deformation control of the flexible suspension system based on various loads, vertical deformation, temperature effects, etc. has become an engineering problem. The restraint release in the internal rigid and external flexible structure connection and the deformation absorption double-layer structure construction control technology method have been innovatively developed based on systematic research and analysis of a large amount of calculation data. The development of five types of flexible connection sliding bearing devices has been achieved to control. The segmented installation technology of the building height partition and the reverse construction of the curtain wall support structure has been adopted in the installation process of the peripheral flexible structure system, which realizes the lean installation of the ultrahigh altitude and complex working conditions of the curtain wall support structure. The "main operating platform structure" and the "sub-operation platform structure" constitute a modularized integrated, computer-synchronized, and intelligently controlled descending installation platform system which is adopted as main technical method. The digital model analysis technology can be used to realize the precise installation of more than 140,000 m^2 area and more than 20,000 glass curtain walls at one time [48].

7. Innovation in Shanghai Tower

7.1. Project Overview. The Shanghai Tower is a skyscraper integrating commerce, exhibitions, offices, hotels, and tourism at a height of 632 meters. It is the only building in China that has exceeded 600 meters in height. The design of the building breaks through the horizontal city tradition, and a double-layer glass curtain wall system is adopted to construct a new concept of a vertical city, which has achieved the goal of a world-class quality project of green building, wisdom, and humanity [49, 50].

7.2. Innovative Technology. The Shanghai Tower breaks through the traditional cascading concept in architectural design. It has set up 9 vertical communities and 21 aerial activity squares at different heights and regions and built a new vertical city new model of super high-rise buildings. The vertical city created by the Shanghai Tower is to form numerous public aerial activity squares between the enclosed double-glazed curtain walls, which is used for citizens to communicate in the aerial public activity square. In terms of structural design, a giant structural system integrating the main structure and the suspension structure was used innovatively. This rigid-flexible structural system was applied for the first time in super high-rise building construction [51, 52].

The architectural geometry of Shanghai Tower is determined based on comprehensive aerodynamic test research. Through wind tunnel tests of many building models with different rotation angles, a curved building exterior with 120° torsion has been innovatively designed. On the basis of effectively reducing the effect of wind load by 24%, the best combination of aesthetics and wind engineering has been realized.

The new mega structure system has been adopted in the Shanghai Tower. The connection point between the outer flexible structure system and the internal rigid structure system is neither a simple hinged connection nor a simple rigid connection, and its forces are very complicated. Five types of connection methods have been determined to satisfy the restraint release and deformation absorption between interconnections based on systematic analysis and research [53]. For the five connection methods, five types of flexible connection sliding bearing devices have been innovatively developed to effectively ensure the deformation coordination of the two different rigid and flexible structural systems in complex working conditions. The stainless steel and chromium-molybdenum alloy steel have been adopted in the sliding bearing device to make the antifriction shell, copper base material inlaid alloy to make the slip ring and nanodiamond coating, which meets the requirements of high precision, high performance, and high-quality friction performance. The synergistic effect of the innovative new suspension structure system and the sliding bearing system realizes the "vertical city" function of the double-skin curtain wall [54].

7.3. Digital Construction. A super high-rise digital construction technology system composed of digital model analysis and calculation, special technology platform, collaborative management and control platform, operation and maintenance management platform, etc. has been established in the Shanghai Tower. Fine digital design, full-process digital construction, and efficient digital operation and maintenance run through all the main links of project construction, achieving efficient control of the control elements of project construction, and open a new model of super high-rise digital construction [55, 56].

7.4. Green Construction. Shanghai Tower took the lead in establishing a green super high-rise building technology system with 600-meter level [57]. Integrating new green building technologies, the energy saving rate reaches 54.3%, the water saving rate reaches 43%, the utilization rate of underground space is 14 times, and the annual carbon emission is reduced by 25,000 tons, which created the world's first super high-rise building with dual certification of the highest level green building of Chinese three stars level and US LEED-CS standards.

7.5. Humanistic Construction. Many innovative approaches have been integrated in the Shanghai Tower in terms of humanities. During the operation and construction of Shanghai Tower, a strong humanistic atmosphere has been built in the public activity space of the "vertical city." The party building activity room in the building, Shanghai Eyes, Guanfu Museum, top sightseeing hall, Michelin restaurant, and sky library, as well as Chinese gardens, landscapes, ceramics, stone carvings, cloisonné, glazed walls, celebrity sculptures, etc., create a cultural environment, which makes Shanghai Tower a unique super high-rise building [58, 59].

8. Conclusions

Looking forward to the development of super high-rise building construction technology, building a digitally driven construction technology system, and striving to change traditional construction methods to comprehensively improve the level of engineering construction have become an inevitable trend in the development of construction technology. The ultimate goal of the digital construction technology system is to realize the whole process of virtual simulation construction on the computer. Intelligent construction will be the most effective way to achieve high-quality development in the construction industry in the future. Digital construction technology can promote a qualitative leap in the construction industry and help China transform from a large construction country to a construction power.

Data Availability

No data were used to support this study.

Conflicts of Interest

The authors declare no conflicts of interest.

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References

[1] J. Gong, T. Fang, and J. Xia, "Construction key technology development of super high-rise building in China," *Construction Technology*, vol. 47, no. 6, pp. 19–25, 2018, in Chinese.

[2] P. Li, "Learning Lubuge experience-speech at the national construction work conference," *Construction Enterprise Management*, vol. 12, pp. 6–10, 1997, in Chinese.

[3] M. Zhao, J. Zhang, and J. Cai, "Visual preference evaluation on urban landmarks in the process of urbanization: a case study of Shanghai Oriental Pearl Radio & TV Tower," *Journal of Asian Architecture and Building Engineering*, vol. 20, no. 5, pp. 493–501, 2021.

[4] J. Chen and J. Zhu, "Spherical reticulated shell production technology of the Oriental Pearl TV Tower," *Architectural Technology*, vol. 25, no. 8, pp. 463–485, 1994, in Chinese.

[5] D. Huang, L. Zhu, Q. Ding, X. Zhu, and W. Chen, "Aeroelastic and aerodynamic interference effects on a high-rise building," *Journal of Fluids and Structures*, vol. 69, pp. 355–381, 2017.

[6] T. Campanella, "Rising at the heart of Shanghai's new business district, the Jin-Mao-Tower designed by SOM reflects the new face of China," *Architectural Record*, vol. 188, no. 1, pp. 82–89, 2000.

[7] D. Wu, J. Zheng, Y. Chen, and L. Sheng, "Study on concrete technology of pumping high-strength concrete to super height of 492m for Shanghai world financial center," *Building and Construction*, vol. 30, no. 4, pp. 237–241, 2008, in Chinese.

[8] R.-h. Yi, "Practice and experience of Canton tower project management," *Frontiers of Engineering Management*, vol. 3, no. 1, pp. 74–79, 2016.

[9] W. Xiong, D. Zhou, and W. Wang, "Design and analysis on structural stability of Guangzhou Tower," *Building Structure*, vol. 42, no. 6, pp. 13–15, 2012, in Chinese.

[10] J. Gong and H. Zhou, "Key technology for structure construction of Shanghai tower," *Building and Construction*, vol. 36, no. 2, pp. 91–101, 2014, in Chinese.

[11] A. Kaplan-Seem, "Tower in Shanghai named best tall building," *Architectural Record*, vol. 197, no. 1, p. 24, 2009.

[12] R. Reid, "Cagelike frame will support Shanghai tower's twisting curtain wall," *Civil Engineering*, vol. 82, no. 3, pp. 14–16, 2012.

[13] J. Wang, S. Yu, and H. Han, "Super deep foundation construction technology of 88-storey Jin Mao Building," *Building and Construction*, vol. 20, no. 1, pp. 9–12, 1998, in Chinese.

[14] Q. Li, T. Zhou, and X. Zhou, "Construction technology for main tower deep foundation of Shanghai world financial center," *Building and Construction*, vol. 28, no. 2, pp. 81–83, 2006, in Chinese.

[15] Y. Li, "Construction technique of testing piles in Shanghai Tower," *Chinese Journal of Geotechnical Engineering*, vol. 32, no. S2, pp. 379–382, 2010, in Chinese.

[16] Y. Tang and X. Zhao, "121-story Shanghai Center Tower foundation re-analysis using a compensated pile foundation theory," *The Structural Design of Tall and Special Buildings*, vol. 23, no. 11, pp. 854–879, 2014.

[17] Y Tang and X. Zhao, "Deformation of compensated piled raft foundations with deep embedment in super-tall buildings of Shanghai," *The Structural Design of Tall and Special Buildings*, vol. 24, no. 7, pp. 521–536, 2015.

[18] J. Zhu, "Construction technology of diaphragm wall for main building of Shanghai center tower," *Chinese Building Construction*, vol. 32, no. 4, pp. 325–327, 2010, in Chinese.

[19] S. Ren, "Construction technology of ultra-deep underground continuous wall in Hongqiao Road block of Shanghai Xujiahui Center," *Architectural Engineering Technology and Design*, vol. 6, no. 20, pp. 2118–2120, 2018, in Chinese.

[20] L Xu and L Hua, "Construction technology applied to Shanghai tower super large foundation pit combining bottom-up for main tower and top-down for podium," *Building and Construction*, vol. 5, pp. 808–810, 2006, in Chinese.

[21] X. Wang, "Analysis of retaining wall deformation for deep and big foundation pits podium in Shanghai Tower," *Chinese Journal of Rock Mechanics and Engineering*, vol. 31, no. 2, pp. 421–431, 2012, in Chinese.

[22] G. Liu and W. Wang, *Manual of Foundation Pit Engineering*, China Architecture & Building Press, Beijing, China, 2nd edition, 2009.

[23] DG/Tj08-2364-2021, *Technical Standard for Micor-Deformation Control of Excavation Engineering*, Tongji University Press, Shanghai, China, 2021, in Chinese.

[24] T. Cao, "Construction technology for concrete structure of Jinmao high-rise building in Shanghai," *Concrete Technology*, vol. 28, no. 5, pp. 28–30, 1999, in Chinese.

[25] Y. Zhang, Y. Chen, J. Zheng, and H. Ma, "Study on pumping technology for super mass concrete 36900 m3 in volume and its application to the main tower foundation of Shanghai world financial center," *Building and Construction*, vol. 27, no. 11, pp. 1–3, 2005, in Chinese.

[26] P. Zhan, J. Xu, J. Wang, and C. Jiang, "Multi-scale study on synergistic effect of cement replacement by metakaolin and typical supplementary cementitious materials on properties of ultra-high performance concrete," *Construction and Building Materials*, vol. 307, Article ID 125082, 2021.

[27] D. Wu, L. Hua, and J. Chen, "Study on key technology for super high pumping concrete construction management," *Construction Technology*, vol. 38, no. 3, pp. 929–932, 2016, in Chinese.

[28] D. Wu, J. Chen, Z. Yang, and J. Shen, "Research on the key technology of the performance of super high pumping concrete materials," *Coal Ash*, vol. 28, no. 3, pp. 39–42, 2016, in Chinese.

[29] J. Gong, W. Cui, and Y Yuan, "Monolithic pouring of the foundation slab of the 632-m high Shanghai tower," *Structural Concrete*, vol. 18, no. 3, pp. 381–396, 2017.

[30] J. Zuo, T. Fang, Y. Chen, J. Ji, and H. Zhou, "Study on control of shrinkage cracking of concrete," *Building and Construction*, vol. 43, no. 6, pp. 1150–1152, 2021, in Chinese.

[31] J. Gong and Y. Wang, "Introduction of code for construction of concrete structures GB50666-2011: cast-in-situ concrete," *Construction Technology*, vol. 41, no. 361, pp. 8–14, 2012, in Chinese.

[32] D. Li, R. Zhang, and Y. Zhang, "GB50204-2015," *Code for Quality Acceptance of concrete Structure Construction*, China Architecture & Building Press, Beijing, China, 2015, in Chinese.

[33] T. Geng, "Planning and application of core construction equipments to over 300 m super high-rise building constructione," *Building and Construction*, vol. 40, no. 90, pp. 1572–1575, 2018, in Chinese.

[34] Y. Lu, J. Gao, and M. Wang, "Application of formwork technology in super high rise building engineering," *China Construction Metal Structure*, vol. 14, no. 6, pp. 85–90, 2014, in Chinese.

[35] P. Qin, "Research on synchronous lifting technology of steel column type integral climbing steel platform formwork," *Building and Construction*, vol. 42, no. 7, pp. 1208–1211, 2020, in Chinese.

[36] Y. Zhu, X. Fu, and P. Qin, "Construction technology for hydraulic climbing integral steel platform formwork supported by cylinder racks crossing over cantilever truss layer," *Building and Construction*, vol. 36, no. 1, pp. 43–46, 2014, in Chinese.

[37] X. Fu, J. Ma, and P. Qin, "Installation of hydraulic climbing integral steel platform formwork supported by cylinder racks," *Building and Construction*, vol. 36, no. 1, pp. 39–42, 2014, in Chinese.

[38] X. Fu, Y. Li, Y. Liang, and L. Huang, "Technical study and application of integral climbing steel platform formwork equipment alternately supported by steel columns and tubular frames," *Building and Construction*, vol. 36, no. 4, pp. 390–394, 2014, in Chinese.

[39] Y. Huang, X. Fu, and F. Fang, "Truss layer construction equipped with integral steel platform formwork alternately supported by steel columns and cylinder racks," *Building and Construction*, vol. 36, no. 1, pp. 54–56, 2014, in Chinese.

[40] X Zhang and X Fu, "Key technology of integral steel platform formwork equipment overhead spanning truss layers for construction of core-tube of super tall building," *Building and Construction*, vol. 40, no. 2, pp. 210–212, 2018, in Chinese.

[41] X. Zhang, "Application of integral steel platform formwork equipment supported by steel column to Shanghai international airlines service center tower construction," *Building and Construction*, vol. 37, no. 11, pp. 1304–1306, 2015, in Chinese.

[42] L. Xu, L. Hua, and G. Zhu, "Design and application of overhead underpinning platform system to construction elevator in ultra tall building," *Building and Construction*, vol. 36, no. 6, pp. 720–722, 2014, in Chinese.

[43] X. Wang, Y. Liang, Y. Li, and G. Huang, "Design calculation and analysis of hydraulic-climbing integral steel platform formwork alternately supported by tow tubular frames," *Journal of Tongji University*, vol. 36, no. 4, pp. 383–389, 2014, in Chinese.

[44] J. Gong, Y. Zhu, and Y. Huang, "JGJ459-2019," *Technical Standard for Self-Climbing Integrated Scaffolding and*

Formwork Equipment with Steel Platform, China Architecture & Building Press, Beijing, China, 2019, in Chinese.
[45] J. Wu, Y. Bian, and M. Xu, "Synchronizing lifr for the integrated antenna mast of bright oriental pearl radio and TV tower," *Building and Construction*, vol. 24, no. 1, pp. 44–49, 1996, in Chinese.
[46] D. Zhou, J. Han, H. Yang et al., "Structural design of Guangzhou tower," *Building Structure*, vol. 42, no. 6, pp. 1–12, 2012, in Chinese.
[47] K. Ye and Q. Fan, "Technology for construction of JinmaoTall building in Shanghai," *Construction Technology*, vol. 28, no. 1, pp. 52–55, 1999, in Chinese.
[48] B. Jia, "Key technology for construction of steel support structure for flexible suspension type curtain wall," *Building and Construction*, vol. 39, no. 10, pp. 1505–1508, 2017, in Chinese.
[49] M. Strabala, "Shanghai tower," *Space*, vol. 573, pp. 68–73, 2015.
[50] J. Gu, "Shanghai tower brief introduction," *Architectural Practice*, vol. 1, no. 11, pp. 26–35, 2018, in Chinese.
[51] M. Jover, "Shanghai, a garden at the foot of the towers," *Connaissance Des Arts*, vol. 34, no. 661, pp. 122–127, 2008.
[52] J. Ding, S. Chao, H. Wu, Z. He, Q. Zhang, and J. Li, "Key technology of green building in the Shanghai Tower structural design," *Journal of Building Structures*, vol. 38, no. 3, pp. 134–140, 2017, in Chinese.
[53] L. Fang, "Environmental impact assessment in the whole process of super high-rise building construction," *Fresenius Environmental Bulletin*, vol. 30, no. 6B, pp. 7923–7932, 2021.
[54] J. Ding, Z. He, and J. Li, "Design and study of super suspend curtain wall support structure of Shanghai tower," *Journal of Tongji University*, vol. 44, no. 4, pp. 559–566, 2016, in Chinese.
[55] W. Peng, "Digital design and construction of Shanghai tower," *Time Architecture*, vol. 11, no. 5, pp. 82–89, 2012, in Chinese.
[56] J. Chen and D. Zhang, "Application of BIM technology in Shanghai tower," *Building Structure*, vol. 42, no. 3, pp. 13–15, 2012, in Chinese.
[57] H. Zhang and X. Zhou, "Application of green building technology in Shanghai tower," *Sichuan Building Science*, vol. 40, no. 6, pp. 277-278, 2014, in Chinese.
[58] Z. Fan, H. Fan, and J. Han, "Super-high green building techniques characteristics of Shanghai tower," *Construction Science and Technology*, vol. 12, no. 14, pp. 28–31, 2013, in Chinese.
[59] X. Xue, ""Shanghai center": interpretation from art and humanities' perspective," *Shanghai Artist*, vol. 13, no. 5, pp. 17–21, 2013.