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Key Technologies in the Structure of Shanghai Tower
上海中心大厦结构工程关键建造技术

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Abstract

As the tallest building in China and the second tallest building in the world, Shanghai Tower is a high-rise building with complicated structures which are very difficult to construct and require innovative building solutions. With a view to providing reference for similar projects, this paper gives a description of the construction process of the large scale ultra-deep foundation pits in soft soil, construction of super-large volume of concrete and the steel-concrete structures of the building and summarizes the key technologies for the construction of the project.

Keywords: Pile foundation construction, foundation pit construction, foundation construction, concrete structure construction, steel structure construction, curtain-wall steel structure construction.

摘要

上海中心大厦为中国第一、世界第二高楼，其结构体形复杂，施工难度巨大，许多建造技术需要采用创新的方法来解决。通过对软土地基上的超大超深基坑工程、超大体积混凝土工程、钢-混主体结构工程建造过程的论述，系统总结了建造过程中的关键技术，以期为同类工程提供借鉴。

关键词：桩基工程、基坑工程、基础工程、混凝土结构工程、钢结构工程、幕墙钢支撑工程

Brief introduction to the project

The 632-meter high Shanghai Tower includes 5floors underground and 124 floors above ground (see Figure 1). The structure above ground is a steel and reinforced concrete system. The vertical structure consists of a concrete core wall and mega-columns and the level structure includes floor steel beams, floor trusses, belt truss, outrigger trusses and composite metal decks. The tower roof is a steel framed spire. The exterior double skin curtain wall system suspended by the truss bracing system is equipped with clear-tempered laminated glass.

Long bored cast-in-place piles with diameter of 1000 mm and length up to 86.65mare used for the tower, while long bored cast-in-place single pile below the column with diameter of 700mm and length up to 62mm are adopted for the podium. The underground structure is a reinforced concrete framed structure. Top-down construction method was introduced from the tower to the podium area. The depth of excavation of the foundation pit of the tower is 33.1 meters which is supported by 6 pieces of reinforced ring beams and round diaphragm wall with inner radius of 121m, thickness of 1.2m and depth of 50m. The depth of excavation of the foundation pit for

工程概况

本工程地下5层，地上124层，总高度632m（请见图1）。上部结构为钢混结构体系，竖向结构包括钢筋混凝土核心筒和巨型柱，水平结构包括楼层钢梁、楼面桁架、带状桁架、伸臂桁架以及组合楼板，顶部还有屋顶皇冠。外墙采用双层玻璃幕墙，外幕墙通过幕墙支撑体系悬挂于结构上。

主楼钻孔灌注桩桩径1000mm，最深深度86.65m；裙房一柱一桩桩径1000mm，抗拔桩桩径700mm，深度62m。地下结构为钢筋混凝土框架结构体系，主楼顺作裙房逆作。主楼基坑挖深33.1m，采用圆环形地下连续墙加6道环形圈梁围护，地墙内径121m，墙厚1.2m，墙深50m。裙房挖深26.7m，“两墙合一”的地墙，墙厚1.2m，墙深48m。主楼基础底板厚度6.0m，混凝土强度等级C50R90。

水文地质概况(请见表1)

超长钻孔灌注桩施工关键技术

深厚砂层钻孔灌注桩成孔施工技术

采用正反循环结合钻孔工艺，上部粘土层(25米深度)正循环成孔，下部泵吸反循环成孔。选用优质纳基膨润土人工造浆，配备ZX-250型除砂机对循环泥浆进行除砂。采用GPS-20型钻机、三翼双腰箍钻头，以

Stratum No. 土层序号	Name of stratum 土层名称	Thickness of stratum 层厚	Gravity γ(kN/m³) 土层重度	Peak value of setting 固快峰值		Lateral permeability coefficient(cm/sec) 水平渗透系数	Vertical permeability coefficient(cm/sec) 竖向渗透系数
				C (kPa)	φ (°)		
②	powdered clay 粉质粘土	0.3~1.61 2.80	18.6	19	19.5	1.83x10-7	1.17x10-7
③	silt and powered clay 淤泥质粉质粘土 sand and powdered clay 夹砂质粉土	4.00~5.21 6.50	17.7	9	21	3.49x10-7	1.73x10-7
④	silt clay 淤泥质粘土	6.60~7.89 9.10	16.8	10	13	1.15x10-7	5.19x10-8
⑤1a	caly 粘土	2.50~3.74 5.20	17.6	12	12.5	1.31 x10-7	6.27x10-8
⑤1b	powdered clay 粉质粘土	2.00~4.22 9.00	18.2	16	17	1.27x10-7	6.75x10-8
⑥	powdered clay 粉质粘土	1.40~4.16 5.30	19.7	45	19	1.33x10-7	8.27x10-8
⑦1	powdered soil and powdered silt 砂质粉土夹粉砂	5.30~7.96 12.00	18.8	4	34.5	1.86x10-4	1.44x10-4
⑦2	silt 粉砂	26.90~32.16 35.80	19.1	3	35.5	8.66x10-4	5.41x10-4
⑨1	sandy silt 砂质粉土	5.80~8.92 12.50	18.9	4	35	1.69x10-4	1.22x10-4
Note: pressure-bearing water for Stratum No. ⑦ are linked with that for No.⑨. There are about 5 meters long of the foundation for the tower located at the pressure-bearing water. While only one meter long of the foundation for the podium located at the pressure-bearing water.. 备注：第⑦、第⑨层承压含水层相连，主楼基础最深处进入承压含水层组近5.00m，裙房基础最深处进入承压含水层1m。							

Table 1. Table of Strata
表1. 地层参数表

the podiums is 26.7 meters. The diaphragm wall for both podiums and the tower, with thickness of 1.2m and depth of 48m, was used in this project. The thickness of the reinforced concrete foundation slab for the tower is 6 meters which employs concrete C50R90.

Hydro-geological conditions of the project (see Table 1)

The key construction technologies for deep bored cast-in-place piles

The construction technologies for the bored cast-in-place piles in deep sand bed

Both positive circulation and reverse circulation boring are introduced for the bored cast-in-place piles in this project. Positive circulation technology is adopted in the course of boring for upper clay bed (within the depth of 25 meters) from ground, while pump suction reverse circulation boring is employed for the lower clay bed. High-quality bentonite is used for grouting material. The sand removing from the grout is done by a ZX-250 type sand-removing machine. The GPS-20 boring machine and drill bit with tri-winds and double-stirrups are used in the construction in order to meet the requirement for both depths of boring and the straightness within 1/150.

The pile-end post grouting technologies

During the grouting, both the quantity of cement and the grouting pressure were properly controlled. The grouting amount and grouting pressure per pile is 4T and 3MPa respectively. Three grouting pipes were pre-placed in the pile which also plays the role of ultrasonic detection pipes (two in service, one standby). The bottom of grouting pipes was connected with a one-way grouter, which was put together with a steel cage into the trench. Meanwhile, the pipes are filled with water so as to prevent leakage of the mortar.

The construction technologies for the construction of super deep diaphragm wall

Construction Technologies of grabbed and milled diaphragm wall

Since the average value of specific penetration resistance Ps for 2 layers in foundation soil ⑦ is 26.91MPa, grabbing and milling trench forming

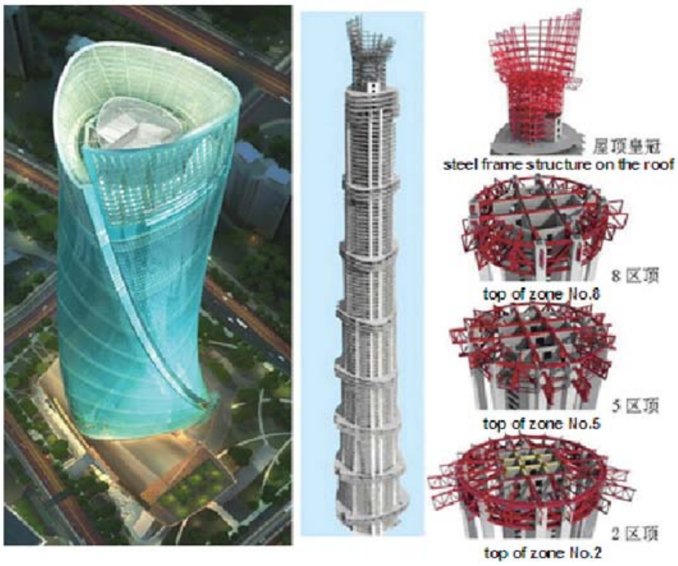

Figure 1. Structure of Shanghai Tower
图1. 上海中心大厦结构

满足成孔深度及1/150的垂直度要求。

桩端后注浆施工技术

采用注浆量、注浆压力双控原则，单桩注浆量4T水泥，注浆压力3MPa。桩身均匀设置3根注浆管(与超声波检测管共用，2用1备)，注浆管下端与单向阀式注浆器相连，随钢筋笼同时下放，并在管内注水以严防漏浆。

超深地下连续墙施工技术

抓铣结合地下连续墙施工技术

由于地基土⑦2层比贯入阻力Ps平均值26.91MPa，采用抓铣结合的成槽工艺。上部30m土体（⑥层及以上土层），用真砂成槽机直接抓取；进入30m深度以下（⑦1层粉砂土）后，用液压铣槽机铣削（宝峨BC32和BC40）。钢筋笼整幅起吊（86T），采用1台400t履带吊和1台260t履带吊双机抬吊。选用锁口管结合“V”形钢板接头，有效防止混凝土绕流。

technologies were adopted in the process of the construction. For the upper part of the soil (soil at ⑥ layer and above), the grabbing trench forming machine was used; for the soil deeper than 30m (below silt sand at layer ⑦), the hydraulic milling trench forming machine (BC32 and BC40) was used. One 400-ton crawler crane and one 260-ton crawler crane were adopted for the hoisting of the reinforced cage with weight of 86 tons. Meanwhile, a V-type steel plate connected with locking pipe was used to prevent bypassing of concrete.

New Techniques for Over-cut Construction

Over-cut technology was successfully tested in the construction of the circular diaphragm wall for the tower. Trenching of Stage 1 was implemented first and then trenching of Stage 2 was cut in between two trenches of Stage 1. The cutter was used directly to cut the concrete of the constructed trench and the connector was formed. This construction technology greatly reduces the possibility of water leaking during the construction.

The key construction technologies for large-scale ultra-deep foundation pits employing top-down & bottom-up methods

The construction technologies for ring-form supportless foundation pit employing top-down method in the middle of the tower

In order to properly control the confined water at the tower area, 12 confining pressure wells with the depth of 55 meters were arranged inside the circular diaphragm wall, while 14 wells of the same kind with the depth of 55meters and 65 meters were respectively arranged outside the circular diaphragm wall. 12 confining pressure wells were then opened inside when the excavation reached -17.5 meters underground. 23 wells of the same kind were then opened outside when excavation reached -28.8 meters underground. The wells were shut 7 days after completion of concrete casting of the base slab.

Four soil borrow platforms were symmetrically setup inside the diaphragm wall for the tower, and the excavations were symmetrically carried out in 4 sections of the foundation pit. Each platform was used for the excavation earthwork in one section of foundation pit (see Figure 2). Both construction methods of basin earthwork excavation and island earthwork excavation were adopted in the excavation of foundation pit with 7 layers of soil deposit. Excavation with Grade-2 slope was conducted when the height of layered soil deposit is over 4 meters. Basin earthwork excavation was mostly applied for No. 1, No. 2 and No. 7 layer of soil deposits, while island earthwork excavation was mostly adopted for No. 3 through No. 6 layer of soil deposits.

The construction technology for the podiums employing bottom-up & symmetry method

At this area, the earthwork excavation in each section was carried out simultaneously. Before the excavation at four corners commenced, the cross-type supporting system (see Figure 3) was accomplished, which effectively controlled the deformation of the diaphragm wall and its effects on surrounding condition and underground pipes. Open excavation was conducted for the first layer of earthwork in each section, which was adjusted according to the traffic route for the construction of the tower. Underground basin earthwork excavation was conducted for the soil deposits through No.2 to No.6 layers. Basin earthwork in the crossing area was symmetrically excavated; the skirt of basin earthwork was reserved as wall supports. The concrete cushion was constructed simultaneously, and then the structural bracing system was constructed subsequently.When the structural bracing system was completed, the earthwork excavation at four

Figure 2. Excavation of the foundation pit of the tower
图2. 主楼基坑开挖

套铣接头施工新工艺

在主楼圆环形地墙中做了套铣接头实验并获得成功，先行施工一期槽段，然后在两个一期槽段中间插入二期槽段，利用铣槽机直接切削已成槽段的混凝土形成接头，止水效果良好。

顺逆作结合的超大超深基坑工程施工关键技术

中部区域主楼顺作法圆环形无支撑基坑施工技术

承压水控制考虑沿环形地墙内侧设置55m降压井12口；外侧设置65m降压井14口、55m降压井14口。基坑开挖至-17.5m后开启降压井，先陆续开坑内的12口井；开挖至-28.8m之后开启坑外降压井，最终坑外共开启23口井。底板混凝土浇筑完成后7天停井。

主楼地墙内侧对称设置4个取土平台，基坑开挖平面分4个区域对称进行，每个挖土平台负责1个区域土方开挖(请见图2)。采用岛盆结合方式分7层进行基坑开挖，分层土体高度大于4m时采用2级放坡。第一、二、七层土以盆式挖土为主，第三～六层土以岛式开挖为主。

周边区域裙房逆作法基坑分区对称施工技术

采用土方分区同步开挖、结构分块同步施工的原则，先行完成“十”字对撑体系（请见图3），再开挖四个角部，有效控制地墙变形以及对周边环境和管线的影响。首层采用明挖，分区结合主楼施工运输路线等进行调整；第2至第6层土方采用盆式暗挖，对称开挖“十”字区域盆底土方，盆边留土护壁，同步跟进素混凝土垫层施工，然后进行结构施工，形成结构支撑体系后开挖四角区域的土方。主楼临时地墙，随土方开挖逐层分区爆破。

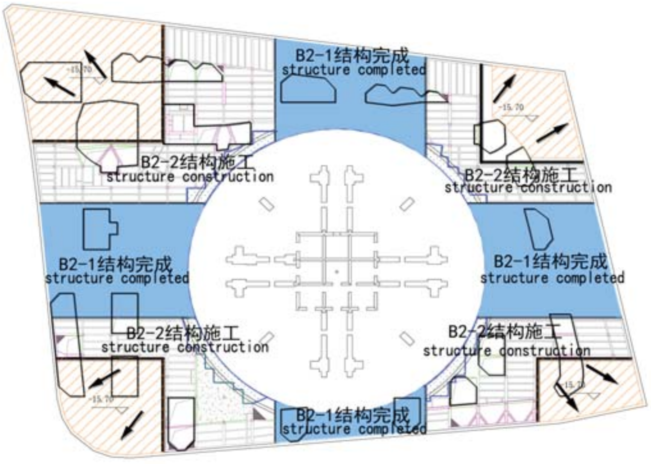

Figure 3. Excavation of the foundation pit of the podiums
图3. 裙楼基坑开挖

corners commenced. The temprory diaphragm wall for the tower was demolished by sections as the excavation progressed.

28 confining pressure wells were arranged outside the diaphragm wall of the tower for the purpose of control of confined water and 18 confining pressure wells with the depth of 45m were added at different spots of the podiums based on characters of these spots. The confining pressure wells were opened when the excavation reached -19.7m and the number of wells was increased with the variation and depth of excavation location. In the end, 32 wells in total were opened. The wells were gradually shut one month after completion of concrete casting of the base slab.

The technology for casting the high-strength concrete to the foundation slab by one time

The technology for controlling the crack in concrete with super large volume, extra length and ultra thickness

The base slab with the length of 121m and thickness of 6m was constructed in this project, which employed a total of 60,000 m3 concrete and used middle- and low-heat cement, large amount of fly-ash and mineral additives as well as high performance poly carboxylate water reducing agent. The consumption of the water was controlled by 160kg/m3. In the concrete curing process, two–layer of films and two- layer of sacks were placed in intervals at the top and real-time temperature was measured so as to guide the construction.

The scheme for the concrete delivery and casting

Depending on the site conditions and the capacity of concrete supply, it was decided to deliver the concrete to the site at a rate of 1000 m3/h so as to shorten the time of concrete casting. It was considered to employ 6 mixing stations at the same time and 405 mixers in a non-stop way so as to finish casting in 60 hours.

Based on the scheme of concrete casting from the center to the surroundings, eight auto pumps with the length of 8 meters and six mounted pumps were arranged at the round foundation pit. Four auto pumps with the length of 56 meters were arranged at the soil borrow platforms (see Figure 4). The foundation concrete was poured from center to edges, which effectively reduced the flowing distance of concrete. Concrete casting was finished first from middle and east part of foundation area and was ended in the west part of the area.

The key construction technology for the rigid shear steel plate at the core cylinder

Two points at one end of the reinforced steel plate were set for installation by one tower crane, and sliding wheel was used to insure the stability of component lifted by the crane.

For the proper concrete flow, several holes with diameter of 150mm at interval of 1,500mm to 2,000mm were drilled in the form of plum blossom in the steel plate. The total area of holes was controlled to be less than 15% of the steel plate, and a reinforced ring was installed around the hole.

The key construction technology for integral steel platform frame system of the core cylinder

The integral steel platform system was adopted in the construction for the core cylinder of the tower (see Figure 5) , which consists of a support system, power system, steel platform system, scaffolding

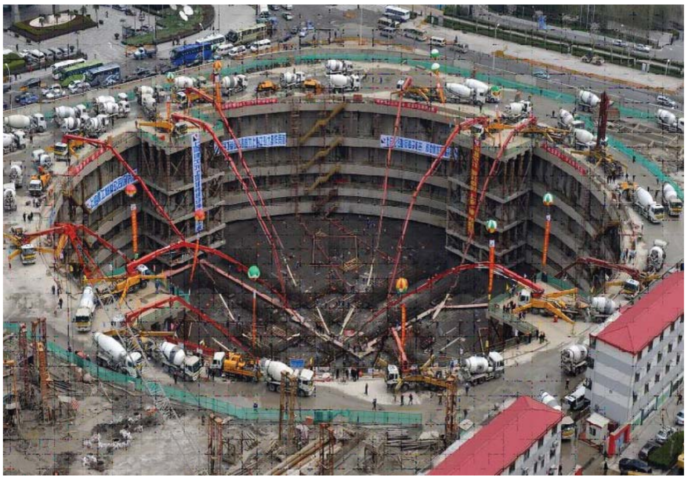

Figure 4. Concrete casting for the base slab of tower
图4. 主楼大底板浇筑

承压水控制利用主楼地墙外的28口降压井，再在裙房地墙内根据分区不同部位特点适当增设45m降压井，总共增加18口。开挖至-19.7m开启降压井，随挖土部位及深度变化逐步增加开井数量，最终共开启32口井。底板混凝土浇筑完成1月后陆续停井。

高强混凝土基础底板一次浇筑技术

超大超长超厚大体积混凝土裂缝控制技术

底板长121m厚6m混凝土总量达6万m3，采用中低热水泥、大掺量粉煤灰和矿物掺合料；采用聚羧酸系高性能减水剂，控制单方用水量在160kg/m3。采取蓄热保温保湿养护法，顶面两层薄膜两层麻袋间隔布置，实时测温指导施工。

混凝土供应及浇筑方案

为缩短浇筑时间，结合混凝土生产能力和场地条件，按1000 m3/h混凝土供应速度，考虑由6个拌站同时供料，配备405辆搅拌车无间歇运输，60h完成浇筑。

混凝土采用由中心向四周退捣方案，在圆形基坑边间隔布置8台48m汽车泵和6台固定泵，取土平台上布置4台56m汽车泵（请见图4）。先集中浇筑圆环中心，再由中心向四周退浇，有效减短混凝土的流淌距离。中部及东部区域先行浇筑完成，最后在西部区域进行收尾。

核心筒劲性剪力钢板层关键施工技术

采用单机一端2点起板和吊装，对不同截面采用滑轮回直措施保证吊装构件的平稳。

钢板上开设直径150mm，间距1500-2000mm的混凝土流淌孔，梅花形布置，对钢板截面的削弱控制在15%以下，开设流通孔部位采用加劲环进行补强。

核心筒整体钢平台模架体系关键施工技术

主楼核心筒采用整体钢平台脚手模板体系施工（请见图5），该体系由支撑系统、动力系统、钢平台系统、脚手架系统和模板系统组成，具备堆放大量材料和设备的承载能力；整体设计以及全封闭构造，提高体系提升和使用阶段的平稳性和安全性；具有实时监控系统可进行全过程监控。

体系通过支撑系统支承于核心筒墙体上，每浇一次混凝土，整体钢平台体系爬升一次。其中钢平台系统是施工人员的操作平台和布料机放置场地，可以堆放整层钢筋；脚手系统悬挂于钢平台下方，为施工人员的上下通道和钢筋绑扎、模板安装的操作空间。

system and formwork system. The platform can support a great mount of materials and facilities during the construction. Its integrative design and closed structure greatly improved the stability and safety of the platform during the construction. The whole process of the work can be monitored by the real-time survey system.

The supporting systems are connected with the core wall. The platform can be raised once the concrete casting is complete. Workers can stay on the platform during working hours. Materials such as steel bars and facilities can also be placed on the platform. The scaffolding system is located below the platform, which can provide more working space and facilitate the workers to conduct works of rebars binding, formwork installation.

The key technology of concrete delivery by concrete pump

The design principle of concrete mix ratio

The concrete mix ratio was designed according to different pumping heights, and specific ratio was taken among 3 different sections. At the first section, from level 1 to level 14, the elevation of which is 0 to 65.8 meters, the self-compaction concrete was supplied. The high-flow concrete was supplied to the second sections with levels from 14 to 84, elevation of which is 65.8 to 393.3 meters. The self-compaction concrete was supplied above level 84, with the elevation of 393.3 meters.

The arrangement techniques for pump pipes and the selection of pumping equipment

Based on pumping to the top only by one pump pile, the concrete delivery was carried out by different pumps. Two trailer-type pumps and two pump pipes were serviced on the ground for concrete delivery, one more pump and pump pipe were standby. One-way valves were installed near the outlet of pump pipe as well as horizontal pipe close to the connection of vertical and horizontal pipe. The vertical pipes were setup in turning pattern so as to reduce the vertical pressure. During the construction, for the pumping level less than 200 meters, the HBT90CH-2135D type pump was adopted; while for pumping level over 200 meters, the HBT90CH-2150D type pump with discharge pressure of 50MPa was used. The theoretical delivery height of an HBT90CH-2150D type pump is 1,000 meters.

The construction technologies for concrete casting

Two sets of concrete spreaders were symmetrically set on the steel platform for concrete delivery in the course of core wall construction. Tremie Pipe was also set with the concrete spreaders to deliver the concrete to desired positions. Mega-column and floor slab was casted simultaneously. Rigid tube was placed in the floor; construction joint was set at the edge of mega-column. When the concrete poured to the mega-column is initially setting, pour the concrete to the floor slab. Concrete pumping technique with water cleaning function was employed. The concrete was delivered to the construction platform via water so as to reduce waste of concrete and the pollution to the environment caused by project construction.

The key installation technologies for extra-large steel structure with complex form

The selection of large tower crane and accessories

For this project, about 100,000 tons of structural steel members and parts were used. The weight of the heaviest structural member is about 94 tons. The steel installation at tower area was conducted by using four sets of M1280D tower cranes and two sets of 300 tons track cranes. The maximum crane radius and lifting capacity of the cranes are 52.5 meters and 100 tons respectively.. The tower cranes were

Figure 5. Integral steel platform
图5. 整体钢平台

混凝土泵送施工关键技术

混凝土配合比设计原则

混凝土配合比根据泵送高度不同分别设计，分为三个区段：0~65.8m（1-14F）采用自密实混凝土、65.8~393.3m（14F-84F）采用高流态混凝土、393.3m以上（84F以上）采用自密实混凝土。

泵管布置工艺及泵送设备的选择

本工程采用一泵到顶的施工方案，在地面布置2台拖泵（另备1台），采用2路泵管（另备1路）进行混凝土输送。泵管在拖泵出口附近、在竖向管和水平管转换处的水平管上设置单向截止阀，竖向立管在立面布置上采用转向弯管布置方式降低垂直压力。200m以下采用HBT90CH-2135D型拖泵，200m高度以上采用泵送出口压力50MPa（目前世界最大）的HBT90CH-2150D型拖泵，理论泵送高度1000m。

混凝土浇筑施工技术

核心筒混凝土采用在钢平台上对称固定布置2台特制布料机，设置固定串筒，布料机通过串筒将混凝土浇至所需部位。巨型柱和组合楼板采用同时浇筑的方法，在楼层中接硬管，在巨型柱边缘设置钢板网施工缝，先浇筑巨型柱混凝土，在巨型柱混凝土初凝前完成组合楼板混凝土浇筑。采用混凝土水洗泵送技术，用水将混凝土送到施工面，减少混凝土浪费和对施工环境的污染。

复杂体形巨型钢结构安装关键技术

大型塔吊选型及配套装置

本工程钢结构总用量10万吨，单个构件最大重量达94t；确定主楼采用4台M1280D塔吊和2台300t履带吊。塔吊最大起吊半径52.5m，最大起重量达100t，采用外挂内爬形式布置在核心筒翼墙外侧中部；300t履带吊布置在地面进行辅助吊装。塔吊支撑装置采用桁架式支撑系统，爬升框由斜撑杆和斜拉索共同支承。

钢结构主要分部安装技术

巨型钢柱单个构件重量最大，分段每节不小于2层，重量不超过94t，每层钢结构框架首先安装巨型钢柱，然后安装其它钢结构部分。

楼面桁架内段采用整体吊装，完成后进行楼层钢梁安装；楼面桁架外段悬挑部分也采用整体吊装，利用钢丝绳及辅助侧向支撑进行临时固定，及时补缺安装斜腹杆。环带桁架先整体吊装内外环带桁架的下弦杆，然后吊装竖杆，并由两端向中间分别安装斜腹杆和中层梁，最后整体吊装内外环带桁架的上弦杆。

installed inside the core wall. The 300-ton crawler crane is located on site to assist the steel installation. The tower cranes are supported by trusses tilted steel bars and steel cables.

The installation technology for the main parts of steel structure
The weight of the heaviest piece for the mega-columns is over 94 tons, and its height is over the height of 2-floor buildings. For the steel structure installation at each floor, the steel member for the mega-column was firstly installed and the rest parts of the steel structure were installed afterwards.

The process of steel installation for floor trusses is as follows: The inside part of floor truss was installed by integral lifting, and then the floor steel beam was installed. The cantilever beam at outside part of floor truss was also installed by integral lifting. The wire rope and lateral support were used for temporary fixation, and then the installation of the inclined bar was supplemented. For the belt trusses, bottom chord bar of both inner and outer truss belt was installed by integral lifting first; then vertical bar was installed; next, the inclined bar and middle beam were installed from two ends towards the middle, respectively. Finally, top chord bar of both inner and outer belt truss was installed by integral lifting.

The process of installation for outrigger trusses is as follows: For the outrigger truss inside the core wall: the bottom chord bar was installed firstly, after the concrete was casted, the rigid reinforced steel column, the middle chord bar and top chord bar were installed subsequently. For the outrigger truss outside core wall: the bottom chord bar esd installed firstly, then the mega-column, the tilted bar, the middle chord bar and top chord bar were installed successively. To properly control deformation, the specific parts for outrigger trusses outside core wall are connected temporarily at an early stage. When the deformation stabilizes, all parts for outrigger truss should be tightly connected.

The installation process for the spire of the tower is listed as follows: Install the octagon steel frame for the truss, then install the steel floor member, accomplish the concrete casting for the main part of core wall and install the reinforced steel structure, finally install the vertical truss and horizontal belt truss successively.

The construction technologies for the flexible suspended steel supporting system of exterior curtain wall
The tower consists of nine zones and eight outrigger trusses. The exterior curtain wall system is fixed with a curtain wall steel structure support system suspended below the floor truss. The curtain wall support system consists of three sections; each is constructed from center to edge (Figure No.6). On the top of the outrigger trusses, a small crane with working arm was installed; On the bottom of the outrigger trusses, the safety operating platform of the hoistable lift was set. The curtain wall support system is installed by the hoist on the operation platform. In a top-down process, the curtain wall support system for each floor is installed as the operation platform moving down.

To meet the requirements of both design and subsequent construction after structural construction, the analysis on the pre-deformation for steel supporting structure of the curtain wall was conducted, which considered the whole construction processes of the curtain wall system.

Conclusion

This paper describes and summarizes the key construction technologies adopted for the construction of Shanghai Tower with a view to providing reference for similar projects in the future.

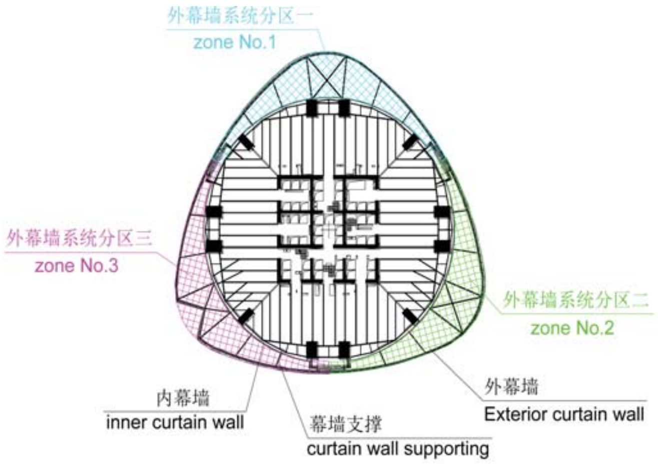

Figure 6. Curtain wall of steel structural support
图6. 幕墙钢支撑结构

核心筒内部的伸臂桁架，随核心筒墙体先施工：先吊装下弦杆，墙体混凝土浇筑后，再吊装劲性钢柱、腹杆和上弦杆。核心筒外围的伸臂桁架，随钢框架安装后施工：先吊装下弦杆，然后依次吊装巨型钢柱，伸臂桁架斜腹杆、中层梁、上弦杆。考虑变形预控制，对核心筒外伸臂桁架的特定部位采用临时连接措施，在变形稳定后择时进行最终连接。

屋顶皇冠安装，先吊装双向桁架以下的八角框架结构，安装相应楼层钢结构，完成核心筒区域混凝土浇筑，再安装双向桁架加强层钢结构，最后依次吊装竖向鳍状桁架以及水平带状桁架。

柔性悬挂外幕墙钢支撑系统施工技术
本工程竖向分9个区设置8个外挑桁架层，外幕墙系统通过悬挂于每个桁架层底部的幕墙钢结构支撑系统进行固定。将幕墙支撑系统分成3个区域，每个区域由中间向两边突台方向施工（请见图6）。在施工区段的上部外挑桁架层顶部，设置动臂小吊车，在上部外挑桁架层的底部，设置可升降的安全操作平台，幕墙钢支撑通过动臂小吊车吊运并在安全操作平台中进行安装固定。每区幕墙钢支撑随安全操作平台逐层下降，从上往下安装完成。

为确保结构施工完成后满足设计和后续工种施工要求，对幕墙钢支撑结构施工过程进行预变形分析，将幕墙等后道工序和深化制作等前道工序一体化考虑。

结语

本文总结了本工程建造过程中的关键技术，以期为同类工程提供借鉴。