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Designing a Megatall for Lateral Stability and Settlement
巨型高层结构的侧向稳定性和变形

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As a megatall building, Suzhou Zhongnan Center will need an efficient lateral system to withstand high wind and seismic loads. A unique "Core-Outrigger-Megaframe" lateral system is used for Zhongnan Center to meet China's code requirements. The foundation system, consisting of a 6.3m-thick mat supported on bored piles, helps support the massive tower and control the settlement. Its tower crown utilizes a concise structural system that delivers architectural elegance and achieves structural efficiency.

超高层结构需要高效的抗侧力体系来抵御风荷载和地震作用。塔楼采用了独特的"核心筒-外伸臂桁架-巨型框架"抗侧力系统以满足中国规范的要求。地基基础由钻孔灌注桩支撑6.3米厚的筏板组成，以达到支撑巨型塔楼和控制沉降量的目的。塔冠通过采用简洁的结构体系，将外部建筑优雅造型和内部结构高效简洁进行了有机结合。

Project Description

The main tower of Suzhou Zhongnan Center is divided into nine zones from bottom to top, including one (1) bottom retail/business zone, two (2) office/SOHO office zones, and six (6) apartment/hotel zones. At the top of tower is a unique crown that is about 100 meters tall. Like most domestic and international supertall buildings, Zhongnan Center tower is a square with chamfered corners in plan and takes a tapered profile vertically, which helps to meet different floor-plate size requirements for a varied program, and more importantly, reduce the tower lateral load (wind and seismic).

Tower Lateral System

The Zhongnan Center lateral system is a "Core-Outrigger-Megaframe" system consisting of three parts: concrete composite core, perimeter megaframe and outrigger trusses (see Figure 3.1). The perimeter megaframe includes supercolumns, corner columns and nine (9) sets of double-layer belt trusses that are distributed along the building's height.

Housing the elevators and MEP spaces, the core forms a 16-cell (4x4) 35-meter square shape in plan, from Zones 1 to Zone 2. The four core corners are cut back at Zones 3 to 5, and the core becomes a four-cell (2x2) rectangle at Zone 6 to 9 (see Figure 3.2). As the main defense line to resist wind and seismic loads, the core is a reinforced concrete structure and provides the stiffness and strength to resist most of story shears and partial overturning moments. Embedded steel columns are provided at the wall corners and intersections to increase wall capacities. The embedded steel also provides a clear load path from outrigger truss to core wall. Steel plates are embedded in the bottom two zones to help reduce the wall thickness and enhance the ductility.

There are eight supercolumns up to Zone 9, and four corner columns up to Zone 8. Supercolumns and corner columns are steel-reinforced concrete (SRC) columns, with built-up steel columns embedded in the jumbo concrete columns. The supercolumns and corner columns work together with nine (9) sets of double belt trusses, including eight (8) sets of

项目概述

苏州中南中心主塔楼从下到上被划分为九个区，其中包含1个底层商业区，2个办公/SOHO办公区和6个公寓/酒店区。塔楼顶部是一个约为100米高的独特的塔冠结构。和国内外大部分超高层建筑一样，中南中心的平面采用切角的形式，竖向呈现锥形轮廓。这样的体型能够满足因不同建筑功能对平面尺寸不同的要求，更重要的是能够减少水平荷载 (风和地震) 对结构的影响。

塔楼抗侧力体系

中南中心水平侧向体系为"核心筒-外伸臂桁架-巨型框架"体系，主要由以下部分组成: 劲性混凝土核心筒，巨型框架和外伸臂桁架三部分组合而成的 (见图3.1) 。巨型桁架包括巨柱，角柱和9道沿结构高度而设置的双层环带桁架。

核心筒在1区和2区形成了一个16网格边长35米的方形区域作为电梯房和机电室。四个核心筒角在3区到5区被切掉，在6区到9区缩进为一个4网格的矩形区域 (见图3.2) 。作为抵抗风和地震作用的主要防线，劲性混凝土核心筒为承担楼层剪力和部分倾覆力矩提供足够的刚度和强度。核心筒墙角和交叉处的内埋钢柱提高了墙的承载

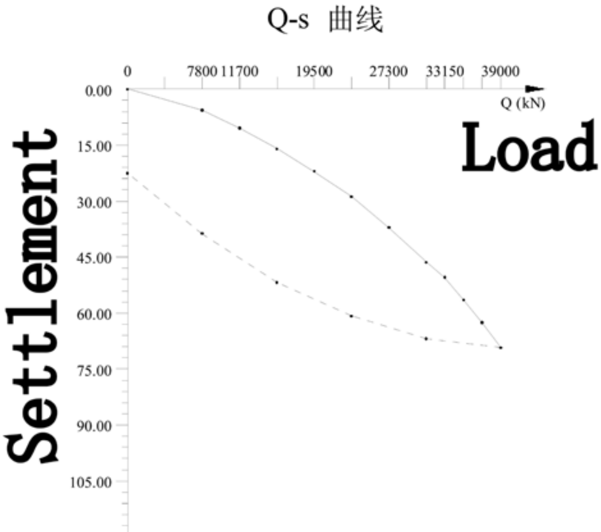

Figure 3.1. Tower Main Lateral System (Source: Thornton Tomasetti);
图3.1. 塔楼主体抗侧力体系 (来源: Thornton Tomasetti)

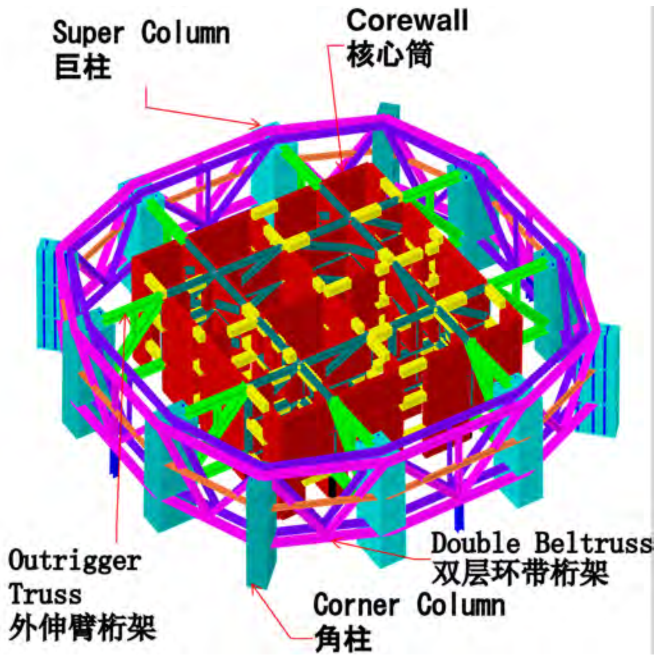

Figure 3.2. Tower Lateral Structure at MEP Levels (Source: Thornton Tomasetti)
图3.2. 塔楼机电层抗侧力结构 (来源: Thornton Tomasetti)

two-story-tall steel trusses and one (1) single-story-tall steel truss, to form the perimeter megaframe that serves as the second line of defense to meet the China Code requirement that a structural system have multiple seismic defense lines. Outer and inner belt trusses are laced together to form a boxed space truss for redundancy and torsional stiffness. Belt trusses also serve to transfer secondary column gravity loads to the supercolumns.

Five sets of two-story-tall steel outrigger trusses are placed at the MEP floors and refuge floors (see Figure 3.3). The location and number of outrigger trusses were extensively studied and optimized. In general, the widely accepted approach to locating outrigger trusses is to distribute the trusses uniformly along the building height in order to reduce building deformation at the top level. Our study shows the outriggers at lower zones are effective in reducing the building's fundamental period, while upper outriggers contribute more to control the story drifts at upper zones. To meet the stringent code-specified story drift ratio requirement, the majority of outrigger trusses are located at the tower's upper zones.

力，同时钢柱还能够为从外伸臂桁架到核心筒提供清晰的传力路径。底部两区设有钢板来减小墙体厚度，提高墙体延性。

八根巨柱贯穿整个9个区，四根角柱贯穿8个区。巨柱和角柱均采用型钢混凝土柱，巨柱中内埋型钢钢。巨柱、角柱和九组环带桁架一起组成了"周边巨型框架体系"。该体系将作为中国规范要求的多道地震防线的第二道防线。内外环带桁架之间提供了有效连接，形成箱型桁架提高抗扭刚度。环带桁架也作为转换结构，将重力柱荷载传递至巨柱。

五组两层高的钢结构外伸臂桁架分别设置在机电层和避难层 (见图3.3) 。工程师对外伸臂桁架的位置和数量做了详细的研究和优化。总体上说，广泛采用的方法是沿高度均匀分布外伸臂桁架以减小结构顶部的变形。分析表明低区的外伸臂能够有效减小结构基本周期，而上部的桁架则对控制高区的层间位移有很大的贡献。为了满足规范设定的层间位移角的要求，外伸臂桁架布置较集中在塔楼高区部分。

塔楼的抗侧力体系是一种简洁高效的结构体系。核心筒、巨柱、外伸臂桁架一起工作，提供了足够的抗侧刚度，满足中国规范中层间位移角小于1/500的要求。其中，核心筒承担了大部分的层剪力，周围巨型框架提供了附加的抗侧承载力。

塔楼楼面系统

与其他超高层结构一样，中南中心的楼面体系采用组合楼盖系统。该体系有混凝土板，压型钢板和钢梁组成。组合楼盖系统与传统的梁板体系相比较，不需要另外支模，从而可缩短施工工期。楼层施工工期是影响超高层结构施工工期的重要影响因素。更重要的是，组合楼板体系重量较轻，从而有利于基础设计，同时地震作用的减小有利于侧向体系结构构件优化。基础和抗侧力体系的优化可以抵消采用组合楼板引起的造价提高。

典型办公区、住宅和酒店的楼板采用125mm厚的组合楼板 (65mm混凝土筑于波高60mm闭口型压型钢板上) (见图3.4a, b) 。机电层和避难层则采用200mm厚钢筋桁架组合楼板 (见图3.4c) 。较厚的楼板提供了足够的强度和刚度，有利于核心筒和巨型框架之间水平力传递。

The tower lateral system is a concise and efficient system, with core, supercolumns and outrigger trusses working together to provide significant lateral stiffness to meet the stringent story drift limit of 1/500 as per China code, while the core takes most of story shear and the perimeter megaframe provide supplementary lateral capacity.

Tower Floor System

Similar to other supertall buildings, the Zhongnan Center tower uses composite floor system. The composite floor system consists of concrete slabs, metal decks and steel floor beams. Compared to a traditional concrete-beam-slab system, a composite-slab system requires less formwork, thus reducing construction time, a critical factor in super and megatall building construction. Moreover, a composite slab system is generally lighter, which would benefit the foundation design and the lateral system structural member optimization, due to the smaller seismic load resulting from a lighter tower weight. The savings from foundation and lateral systems help to offset the relatively high cost of a composite floor system.

The 125-mm-thick composite slab (60 mm of concrete above a 65-mm-deep closed-form metal deck), as shown on Figure 3.4a and b, is used at typical office, apartment and hotel floors. At typical MEP / refuge levels, 200-mm-thick composite slab is built on a steel-trussed formwork system, as shown on Figure 3.4c, to enhance both strength and stiffness of floor plates that are responsible for transferring the lateral forces between the core walls and the perimeter megaframe.

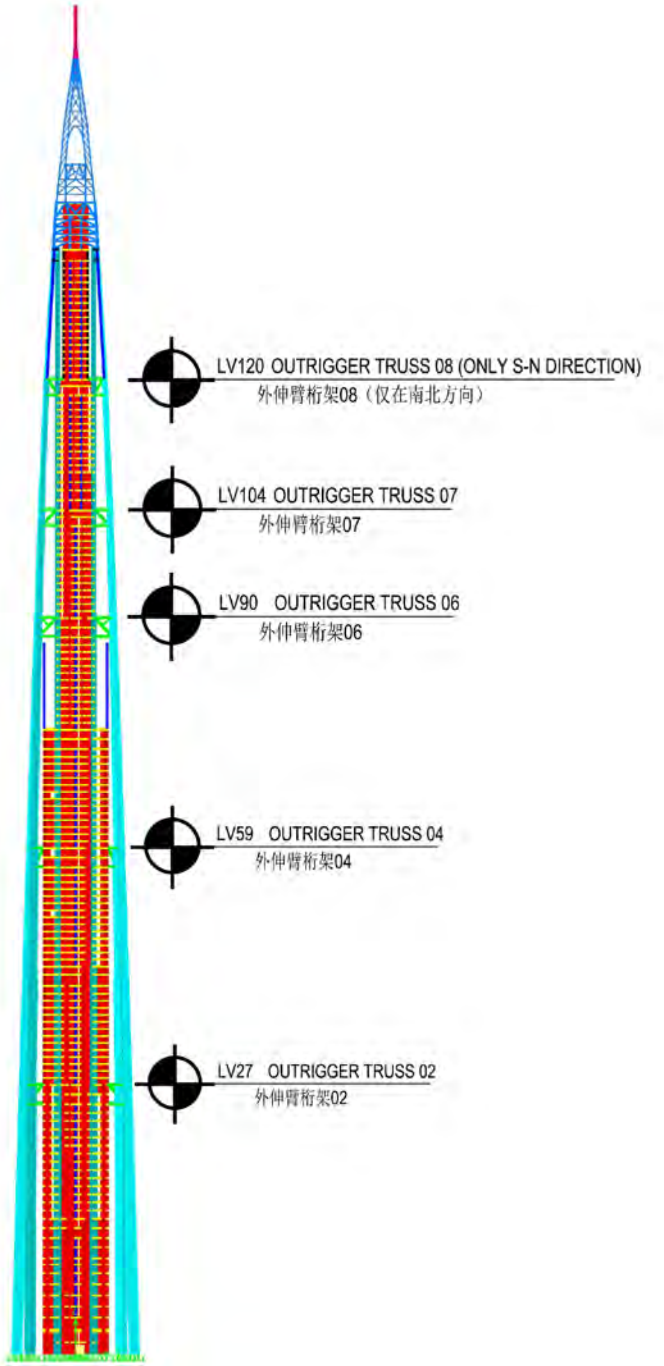

Figure 3.3. Tower Outrigger Layout (Source: Thornton Tomasetti)
图3.3. 塔楼外伸臂分布图 (来源: Thornton Tomasetti)

塔冠系统

中南中心的塔冠部分是整个建筑的重要组成部分，同时塔冠内布置了500到750吨的调谐质量和调谐液体阻尼器，对控制塔楼部分的侧向位移起到重要作用 (见图3.5) 。

中国建筑科学研究院的风洞试验结果表明，在10年一遇的风荷载作用下，酒店区的地面最大加速度为0.274 m/s^2，住宅区为0.185 m/s^2。这些数据均超过了中国规范对酒店区0.25 m/s^2，住宅区0.15 m/s^{2}的要求。中国建筑科学研究院进行了高频测力试验，高频测压试验和气弹试验三种风洞试验。不同风洞试验的最大加速度结果见表3.1。为了满足中国规范的要求，塔楼需布置附加阻尼系统，如调谐质量阻尼器和调谐液体阻尼器等，降低结

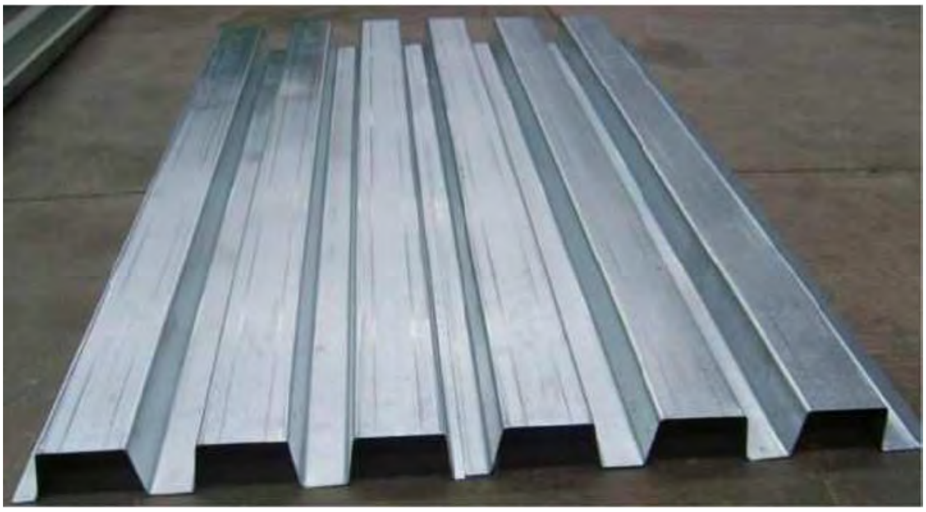

Figure 3.4a. Open-trough profiled composite deck (Source: N.A.)
图3.4a. 开放式槽型组合楼板（来源: 资料不详）

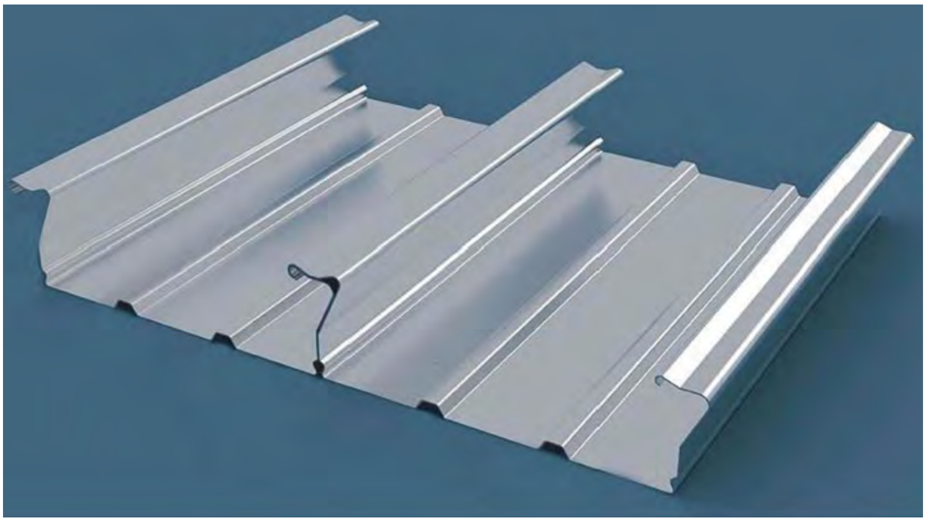

Figure 3.4b. Flat-profiled composite deck (Source: N.A.)
图3.4b. 压型组合楼板（来源: 资料不详）

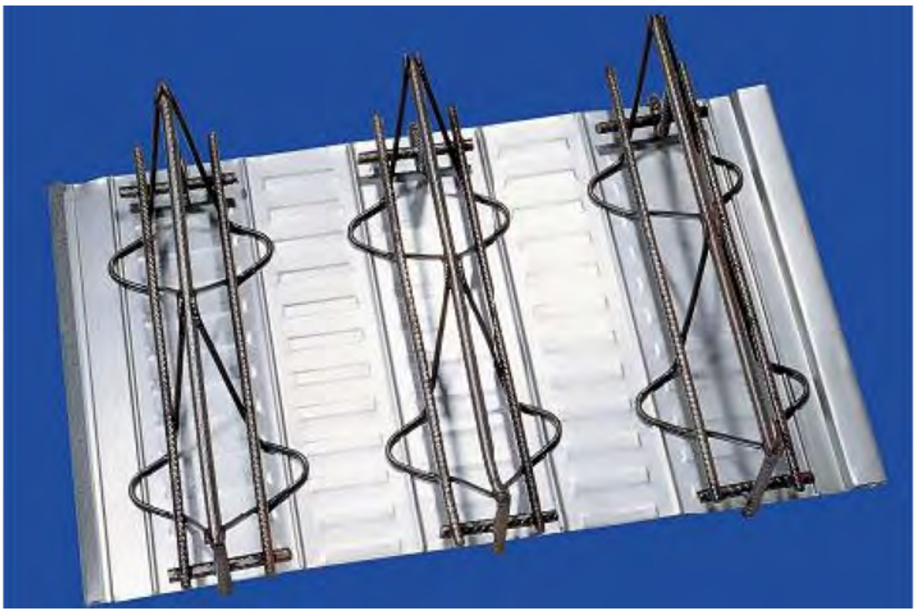

Figure 3.4c. Steel-bar composite deck (Source: N.A.)
图3.4c. 钢筋组合楼板（来源: 资料不详）

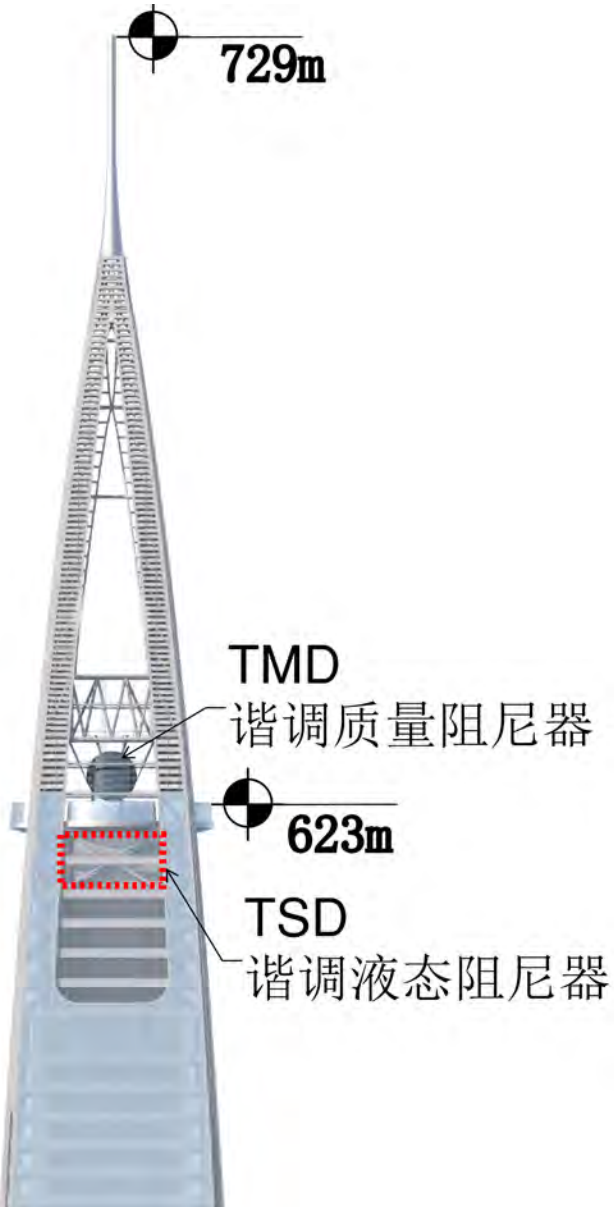

Figure 3.5. Tower Crown 3D Rendering View (Source: Gensler)
图3.5. 塔楼塔冠3D渲染图 (来源: Gensler)

Test Model 测试模型	EL.598 m 标高598米	EL.462.6 m 标高462.6米
	(Hotel) (酒店区)	(Residential) (住宅区)
HFFB高频力平衡	0.274	0.180
HFPI高频压力积分	0.267	0.177
Aero-elastic model 气动弹性模型	0.258	0.185

Table 3.1. Max. acceleration for 10-year return period wind (unit: m/s^2)
表3.1. 十年一遇风荷载结构最大加速度 (单位: m/s^2)

Tower Crown

The Zhongnan Center crown is an important part of the building profile. It also plays an important role to control the deflection of the tower itself by housing a 500 to 750-ton tuned mass damper (TMD) and tuned sloshing damper (TSD), utilizing the firewater-tank space (See Figure 3.5).

According to wind-tunnel test results from the China Academy of Building Research (CABR), the maximum floor accelerations under a 10-year return period wind are 0.274 m/s^2 at the hotel level, and 0.185 m/s^2 at the residential level; these values exceed the China code requirement of 0.25 m/s^2 and 0.15 m/s^2 for hotel and residential, respectively. CABR performed three types of wind tunnel test: high-frequency force-balance (HFFB), high-frequency pressure integration (HFPI) and the aero-elastic model. The maximum accelerations from different wind tunnel tests are shown in Table 1. A supplemental damping system (SDS), like the TMD and TSD, is required to reduce the floor acceleration under wind load and meet the occupant comfort requirement specified in China code. (Table 3.1)

Podium

Located at the southeast corner of tower, the eight-story podium is separated from the tower by a seismic joint. The main podium structure consists of concrete cores at three corners and a

构对风荷载作用下楼面加速度，以满足舒适度要求。

裙房

位于塔楼东南角的八层裙房通过抗震缝与主塔楼隔开。裙房的主体结构主要包括位于三个角部混凝土核心筒和一些塔楼附近的劲性柱 (见图3.6) 。基于建筑对底层少设柱和在商店，宴会区大柱间距的要求，裙房包含了许多大跨度区域，最大跨度约为41米。

为了提供无柱大空间区域，裙房顶部布置了连接角部核心筒巨型桁架，巨型桁架将隐藏在宴会厅的隔墙中。这些巨型桁架将裙房重力荷载传递给三个混凝土核心筒。在裙房底部楼层的商业空间内，布置了支承于巨型桁架的吊柱，以降低楼面结构的跨度，使楼面结构设计更为经济。为了满足无柱大空间要求，宴会厅等大跨区域布置了楼面桁架。

series of composite columns adjacent to the tower (See Figure 3.6). Due to the architectural functional requirement of a column-free area at the ground floor and large column spacing at the retail and ballroom levels, there numerous long-span areas in the podium, with the largest around 41 meters.

To create a large column-free area, megatrusses, hidden in the partitions of the ballroom, are provided at the top levels of the podium to connect the corner core walls. These megatrusses the transfer gravity loads of podium into the three concrete cores. Hangers supported by the megatrusses are added to provide gravity supports to the retail spaces at the podium bottom levels and achieve a more economical design by cutting the gravity framing span. Floor trusses are also provided at the ballroom area to meet the column-free requirement.

A composite slab is also used as the podium floor system to increase the structural efficiency through reducing the building weight, and thereby the steel trusses' costs.

Basement

There are five levels of basement, serving the main functions of MEP, retail and parking. With a typical column grid of 8.5 meters by 8.5 meters, the basement structure is mainly concrete.

A flat slab with a drop panel is used as the floor system at the B3 and B4 levels for parking, while a one-way beam/slab system is used at the B1 and B2 levels to handle heavy mechanical loading and provide more flexibility for the floor openings. To support the heavy loading of landscaping and fire trucks, as specified in the China Loading Code, a waffled two-way beam slab system is used at ground floor.

Geotechnical Conditions and Tower Foundation

Foundation design is always a challenge for tall buildings, due to large vertical forces from gravity and large overturning moments from

Figure 3.6. Tower Podium Plan View (Source: Gensler)
图3.6. 裙楼平面图 (来源: Gensler)

裙房楼面结构也采用了组合楼板，降低结构自重，同时有利于桁架的优化设计。

地下室结构

五层地下室结构的主要功能是为机电用房、商业和停车场提供空间。地下室部分主要为混凝土结构。典型柱网采用8.5m乘8.5m。

地下室B3，B4层主要为停车场，楼板采用无梁楼盖加柱帽的形式。而B1，B2层主要为机电层，楼面采用单向梁板系统，可以承担较大的设备荷载，同时为楼板开洞提供了更多灵活性。为了能够支撑地面绿化景观和消防车荷载，根据规范要求，地面层采用井字梁板体系。

地质情况和建筑基础

对于高层结构来说，巨大的竖向重力荷载和风荷载及地震荷载产生的巨大的倾覆力矩往往使基础设计成为难题。中南中心较差的地下场地情况更加大了设计难度。砂层和粘土层至少要延伸到地表以下120米。针对实际施工情况，基岩是无法达到的 (见表3.2) 。

塔楼基础采用桩筏基础，由719根直径为1.1米的钻孔灌注桩和6.3米的钢筋混凝土筏板组成。为了提高混凝土钻孔灌注桩的承载力和减小沉降量，钻孔灌注桩采用了端注浆技术。核心筒和巨柱底部应力集中的区域，为了布置更多地桩采用了梅花型布桩。钻孔灌

Soil Stratum Succession 土层编号	Soil Stratum Name 土层名称	Bottom of stratum Elevation(m) 土层底层标高(米)	Recommended foundation bearing capacity (kPa) 地基承载力 (kPa)
4	Silty clay 粉质粘土	-2.09~ -5.52	150
5	Sandy silt 砂质粉土	-6.49~ -16.86	160
6	Silty clay 粉质粘土	-17.60~ -31.20	100
(8)1	Silty clay 粉质粘土	-20.96~ -24.42	220
(8)2	Silty clay with sandy silt 粉质粘土与砂质粉土	-28.82~ -33.69	180
9	Silty sand 粉砂	-35.96~ -46.45	250
(10)1	Silty clay 粉质粘土	-49.72~ -61.87	160
(10)t	Silty sand 粉砂	-53.83~ -60.44	220
(10)2	Silty clay 粉质粘土	-56.69~ -72.36	180
11	Sandy silt with silty clay 粉质粘土与砂质粉土	-66.88~ -72.36	280
(12)1	Clay 粘土	-78.03~ -81.83	200
(12)2	Silty clay 粉质粘土	-85.26~ -89.57	280
(13)1	Silty sand 粉砂	-94.53~ -101.44	500
(13)m1	Silty clay 粉质粘土	-89.42~ -97.16	260
(13)m2	Silty clay 粉质粘土	-98.79~ -103.33	350
(13)2	Fine sand 细砂	-141.82~-146.98	650

Table 3.2. Soil Profile
表3.2. 土层剖面

wind and seismic load. The poor site conditions at Zhongnan Center magnify the challenge. Several layers of sand and clay area alternate to at least 120 meters below grade. Bedrock is considered beyond reach for practical construction purposes (see Table 3.2).

A 6.3-meter-thick reinforced concrete mat foundation, supported by 719 bored piles of 1.1 meters' diameter, is used to support the massive tower. End grouting is used at the tips of the tower piles to increase the capacity of cast-in-place (CIP) concrete bored piles and reduce settlement. A staggered-pattern pile layout is used to fit more piles, compared with the square pattern layout for the concentrated stress area under the core and super columns. When bearing at layer (13) m1-Silty clay and (13)2- Fine sand, the piles achieve a capacity of 1,300 to 1,600 tons, with an effective length of 52 to 56 meters.

Differential settlement behavior between the tower and surrounding podium also poses a structural challenge. The water table is just 0.5 to 4.6 meters below grade, while the mat top elevation is at -27 meters. Under the tower footprint, the tower self-weight is sufficient to overcome buoyancy, but the surrounding podium will have to resist net uplift forces due to high buoyancy. The difference in net foundation loads and the soft subgrade conditions will cause differential settlement between podium and tower. To reduce the effects of differential settlement, a carefully selected delayed-pour strip is provided around the interface between tower mat and the podium mat. The mat reinforcement design must consider the mat's internal forces and deformations occurring during different construction stages. Additional reinforcement is added locally at the interface of tower and podium as needed.

Green Building Consideration

Green building design has been accepted globally among governments, developers and design professionals. There are many green building certification programs across the world. LEED, issued by the US Green Building Council, is the most popular one and is widely accepted in China, but China has its own version, the Green Building Evaluation System. In addition to

注桩持力层为(13)m1-粉质粘土和(13)-2细砂层，桩承载力特征值为1300和1600吨，其有效长度为52米和56米。

塔楼和周围裙楼之间的非均匀沉降也是一个结构设计需考虑的要素。中南中心场地水位线在地表以下0.5米到4.6米，而筏板顶部标高为-27米。塔楼自重足以抵抗地下水浮力作用，但是周围裙房则需要布置抗拔桩抵抗净上浮力。不同区域荷载不均匀性和软土路基条件造成塔楼和裙房沉降不均匀。为了减小沉降量差，塔楼筏板和裙楼筏板之间设置了一条后浇带。筏板的配筋设计考虑了在不同施工阶段筏板内力和变形。在塔楼和裙楼的交界处，布置了额外钢筋。

基于绿色建筑的考虑

绿色建筑设计理念被世界各国政府、企业和设计公司所推崇。世界范围内存在着很多绿色建筑的认证项目。由美国绿色建筑协会认证的LEED是最为流行的项目，同时也被中国广泛采用。但是，中国也有自己的绿色建筑评估体系。除了对常规建筑的评估体系之外，2012年5月，中国还颁布了

the Green Building Evaluation System for general buildings, China has also published one for supertall buildings, namely "Technical specification for Green Supertall Building Evaluation," in May 2012. The owner decided to go after the LEED certification and China Green Star certification. A few Green Building credits to which structural engineers can make contributions are listed below:

- All concrete should be pre-mixed.
- More than 60% of building materials are supplied within 500 km of the project site.
- More than 80% of concrete in the main structural members is high-strength concrete, or C50 and above
- More than 80% of structural steel in main structural members is high-strength steel, or Q345 and above
- More than 80% of reinforcement in main structural members consists of high-strength reinforcement, or HRB400 and above

针对超高层结构的"超高层绿色评估技术规程"。业主决定对中南中心采用LEED和中国绿色之星两种认证体系。以下是一些由结构工程师得到的绿色建筑得分:

- 混凝土均采用预拌混凝土。
- 60%以上的建筑材料由500km以内的建筑场地提供。
- 主要结构构件中，80%以上的混凝土采用C50或更高的高强度混凝土。
- 主要结构构件中，80%以上的结构用钢采用Q345或更高的强度。
- 主要结构构件中，80%以上的钢筋采用HRB400或更高的高强度钢筋。

Conclusion

The Zhongnan Center is a complex building with one megatall tower, one long-span podium and one large basement. An efficient "Core-Outrigger-Megaframe" system is used as the tower lateral system; long-span megatrusses are provided between three corner cores to support the podium. A thick mat with long bored piles serves as the foundation system for the heavy tower on the soft soil. The structural systems are crafted to achieve high structural efficiency and integrate with the architectural functions.

结论

中南中心是一座由超高层塔楼，大跨度裙楼和大地下结构组成的复杂建筑。塔楼的水平体系采用了高效的"核心筒-外伸臂桁架-巨型框架"体系。裙房采用了连接三个角部核心筒的大跨度巨型桁架来支撑。位于软土地基的塔楼基础采用厚筏板和钻孔灌注桩。所采用的结构体系在达到了结构高效性的同时满足了建筑功能要求。

References (参考书目):

GB50011-2010, **Code for Seismic Design of Buildings**,

JGJ3 (2010), **Technical Specification for Concrete Structures of Tall Buildings**

Technical Specification for Green Supertall Building Evaluation, May 2012