Title: **Optimizing the Structural Design of the 151 Story Incheon Tower**

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Subjects: Structural Engineering
Wind Engineering

Keywords: Foundation
Optimization
Structure
Supertall

Publication Date: 2014

Original Publication: CTBUH 2014 Shanghai Conference Proceedings

Paper Type:

1. Book chapter/Part chapter
2. Journal paper
3. **Conference proceeding**
4. Unpublished conference paper
5. Magazine article
6. Unpublished

Optimizing the Structural Design of the 151 Story Incheon Tower

151层仁川塔的结构设计优化

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Abstract

The 151 story super high-rise building located in an area of reclaimed land constructed over soft marine clay in Songdo, Korea. The focus of this paper will provide: 1) the structural engineering techniques utilized to optimize the structural and foundation systems of the tower, 2) the different floor framing systems considered, 3) the wind engineering approach to reduce the overall wind forces and to tame the dynamic response of the tower, 4) a description of an additional reliable damping system that is well integrated with the structural and the architectural design concepts to improve the tower's overall behavior, and 5) describe the impact of foundation flexibility on the overall behavior of the tower, through soil structure interaction. The introduction of the damped mega-frame structural system for the 151 story Inchon will be a catalyst in utilizing the latest damping systems and technologies for a "New Generation of Tall Building System"

Keywords: Super High-Rise Building, Structural Optimization, Floor Framing Design, Foundation Design, Foundation Stiffness, Piled Raft

摘要

这个151层的超高层塔楼建造于韩国松岛的一片软性的沿海滩填海地之上。本文将着重谈以下几点: 1) 优化塔楼结构和地基系统的结构工程技术，2) 不同楼层的框架系统，3) 减小建筑风荷载和塔楼形态动力学阻力的风力工程手段，4) 一个与结构和建筑良好整合的阻尼系统，它作为一个可靠耐用的补充措施能够改善塔楼的整体性能，5) 最后是土壤—地基处理对于塔楼整体性能的影响。因为这个151层塔楼是由巨大的框架结构体系建成的，仁川塔会成为对于阻尼系统等新技术利用的催化剂，开启一个"高层建筑体系新纪元"。

关键词: 超高层建筑，结构优化，楼板框架体系，地基设计，地基硬化，筏型桩基。

Introduction

The proposed 151 story Multi-use Inchon Tower is located in the Songdo Inchon Free Economic Zone and founded on new reclaimed land. The 600m tall tower is composed of approximately 30 stories of office floors, 17 stories of hotel & other supporting facilities, 100 stories of residential floors, and several levels of mechanical plant floors. The base of the tower consists of retail, future subway station, and several levels of parking below grade. See Figure 1 for the final rendering of the tower and typical office, residential and mechanical plan arrangements. Several tower massing configurations were studied in details in an effort to improve the overall building response to the overall dynamic excitations. The original tower shape was trapezoidal with very sharp corners. This shape was extremely sensitive to cross wind response and subject to significant lift forces and dynamic excitation. Therefore, in coordination with the principal design architect (Portman and Associate) several treatments were introduced and included:

介绍

这座规划的151层多功能仁川塔位于仁川松岛自由贸易区内的一片填海所得的地块之上。600米高的塔楼有将近30层的办公楼层，17层的酒店及其辅助设施，100层的公寓和几个机械设备层。塔楼的裙房包含了零售区域，规划中的地铁站以及多层的地下停车场。图1是建筑的最终渲染图和标准的办公、公寓和机械层平面图。我们研究了多种塔楼的体量形态来改进建筑总体对于外界力矩的应对能力。塔楼最开始采用的形状是一个角度锐利的梯形。这个形状的风阻非常大，还会产生很大的抬升力和力矩。在和主持建筑师 (波特曼建筑师事务所) 协调后，我们选择以下几个改善策略: 1) 切削塔楼边角; 2) 在建筑体量不同高度开洞; 3) 边缘处理。建筑最后的体量形态如图1所示。

塔楼东西向的结构系统由一个钢筋混凝土的核心筒墙体通过混凝土或复合楼板与两边超尺度的巨柱连接构成，这样能够最大地扩大塔楼的结构宽度。塔楼南北向上通过巨型框架结构来承受荷载，在建筑的3个不同高度处，大约每隔30层会有一个高4层的钢制结构构架来连接两边的钢筋混凝土

1. softening of the tower corners,
2. introducing openings along the building height, and
3. edge treatments.

The final tower massing and geometry are shown in Figure 1.

The structural system of the tower in the east-west direction consists of a reinforced concrete core wall linked to the exterior mega columns with reinforced concrete or composite panels to maximize the effective structural depth of the tower. The lateral load resisting system of the tower in the north-south direction consists of mega-frame structure, where the reinforced concrete core walls are linked by 4-story structural steel trusses at 3 levels at approximately every 30 floors (See Figure 2a). These trusses were augmented with a supplemental damping system, as shown in Figure 12, to reduce the overall vibration response, enhance the overall strength and performance of the tower under extreme events, and ultimately provide reliable damping. The tower superstructure is founded on a pile supported raft foundation consisting of 5.5 meter thick reinforced concrete raft over 172-2.5 meter diameter bored piles with variable lengths and anchored a minimum of 5 meters into soft rock. The vertical and lateral pile testing programs have already been successfully completed utilizing the "O-Cell Method."

Lateral Load Resisting System

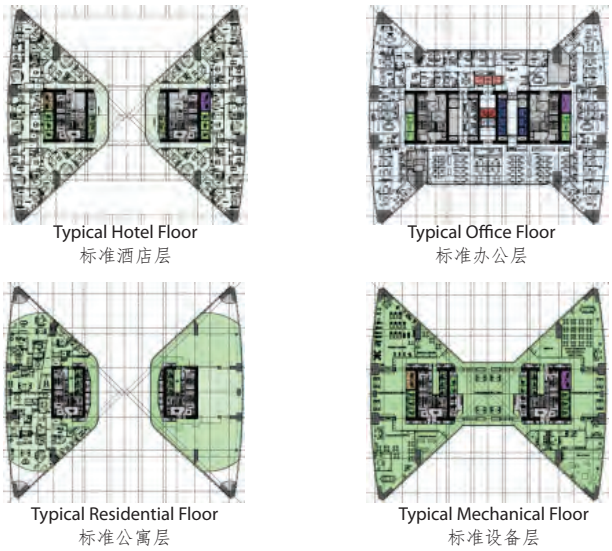
The lateral load resisting system of the tower consists of central reinforced concrete core walls up to level 40 that splits into two cores above level 40. Because of the high aspect ratio of the tower and the sensitivity of the floor airfoil geometry to wind excitation, extensive gravity and wind engineering management was considered during the early development of the structural concept to control the wind forces, building serviceability, and to prevent tension at the extremities of the tower. In addition, the relative column shortening between the vertical elements were also carefully considered to reduce its impact on the structural member performance, architectural detailing, and building services. The gravity load support structure (core walls and columns) are strategically located and proportioned at the building extremities to attract the maximum gravity load to maximize their resistance to lateral loads. In addition, the reinforced concrete core walls and mega-columns are designed on equal stress basis under gravity loads.

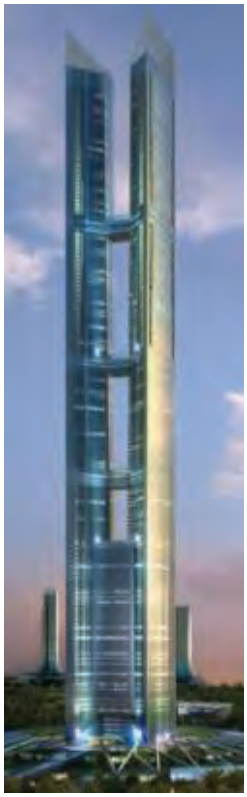
墙体，如图2a所示。这些构架由一个补充性的阻尼系统来加固，详见图12，减少总体风振，增强塔楼在应对极端天气情况下的强度和性能，并维持一个合理的振幅。塔楼整个巨型体量落在一个桩基支撑的5.5米厚钢筋混凝土的筏形地基上，这些桩基共172根，内径2.5米，高度不等，最少也打入地下5米之深。运用了"构件O"我们完成了对于桩基垂直向和侧向的受力测试。

侧向荷载受力系统

塔楼的侧向荷载受力系统包含一个40层的钢筋混凝土核心筒，在40层以上分为两个核心筒。由于塔楼的高表面积系数和应对风力时楼板的翼面效应，在初期结构设计概念的发展中就大量考虑了重力和风的应对策略，以便减小风荷载，提高建筑可用性，并控制塔楼极限点的受力。此外，建筑竖向构件之间的不同柱子的受力形变被仔细设计，以便减小其对于结构性能，建筑细部和塔楼辅助功能的影响。重力承载系统 (核心筒和柱子) 按位置按比例地安排在建筑受力极限值的地方，从而能够承担最多的重力荷载，并增大对侧向荷载的承受能力。钢筋混凝土核心筒和巨柱各自所承受的重力荷载值是均等的。

建筑在东西向上的侧向荷载受力系统由钢筋混凝土核心筒每隔30层通过机械设备层 (高4层，由混凝土或者合成材料的剪力墙体构成) 和两边的巨柱坚实地连在一起 (如图2 所示) 。南北向上的侧向荷载承载系统是通过4层高的钢结构天桥的桁架连接钢筋混凝土核心筒构成，天桥在完善了整个巨型框架结构体系的同时也正好作为一个设备层。天桥设备层的楼板也使用了和核心筒与巨型混凝土巨柱之间一样的多层钢混楼板，这样能够有一个连续的4层楼高的天桥结构桁架将巨柱体系和侧向受力体系相整合，实现了以下几点: 1) 最大化提高了塔楼的刚度; 2) 在极限荷载情况下避免出现沿着整个塔楼高度方向的拉力; 3) 减小核心筒和巨柱之间柱子的荷载形变。图2展示了塔楼巨型结构体系的概念和结构受力





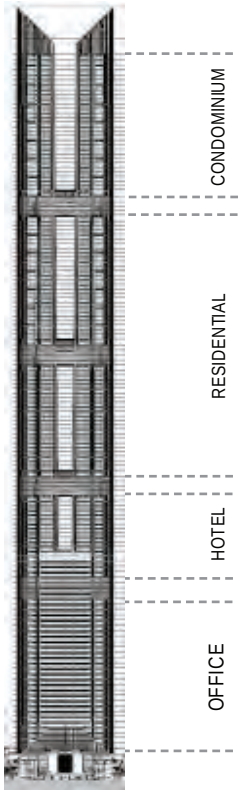


Figure 1.151 story Inchon Tower rendering and typical office, residential and mechanical floor plans
图1: 151层仁川塔的渲染图和办公、住宅、设备标准层平面

The lateral load resisting system of the tower in the east-west direction consists of reinforced concrete core walls that are rigidly connected to the mega-columns at the mechanical levels (every 30 floors) through 4-story reinforced concrete or composite shear wall panels as shown in Figure 2. The lateral load resisting system in the north-south direction consists of reinforced concrete core wall that are rigidly connected by 4-story structural steel bridging trusses, provided at the mechanical levels, to complete the mega-frame structural system. Multi-story reinforced concrete wall panels between the core walls and the mega reinforced columns are provided at the mechanical levels. They provide continuity of the 4-story structural steel bridging trusses and integrate the mega columns in the lateral system to 1) maximize the stiffness of the tower 2) prevent tension along the entire building height under extreme loading conditions, and 3) reduce the relative column shortening between the core wall and the mega-columns. Figure 2 depicts the tower's mega-frame structural concept and outline of the structural system behavior. Alternatively, the mega-frame concept is augmented with supplemental damping to tune the dynamic behavior of the tower under service and extreme loading conditions and to provide reliable damping as shown in Figure 10.

Floor Framing System

While, several floor framing systems were considered for the tower, only two options were evaluated in details for time and cost implications, see Figures 3 and 4. Option 1 consists of a composite floor framing

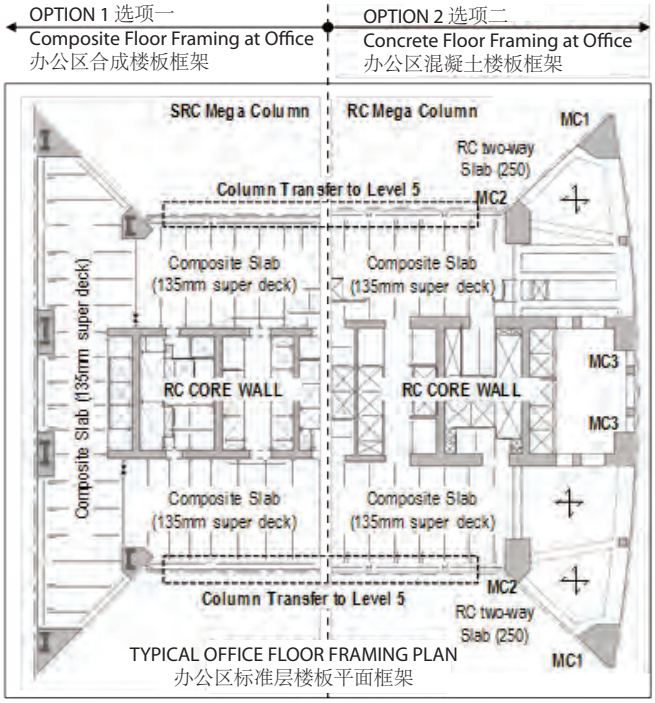


Figure 3. Typical Office and Residential floor framing plans, wall thicknesses, and mega column sizes
图3: 办公和住宅标准层的楼板体系，墙体厚度，和巨柱尺寸

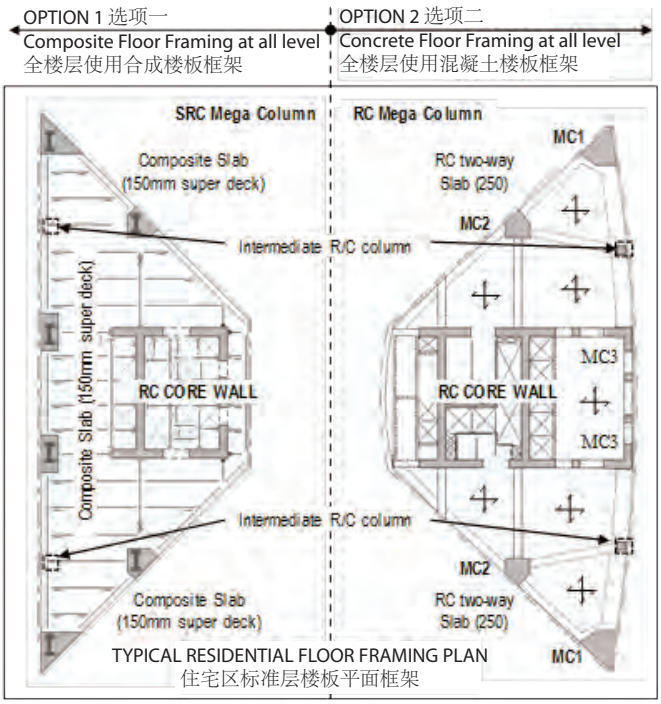


Figure 4. Typical Office and Residential floor framing plans with hollow (bubble deck) flat plate
图4: 办公和住宅标准层的空心 (填充) 楼板体系

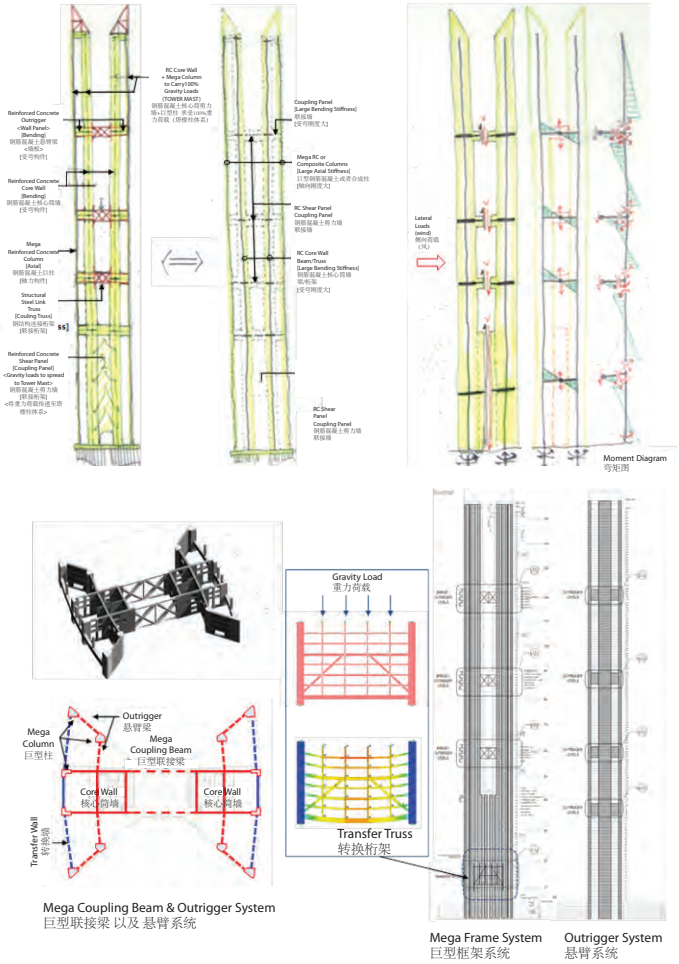


Figure 2. a) Mega-Frame Structural Concept, b) Lateral Load System organization, and Exterior Steel Column Transfer (gravity Columns).
图2: a) 巨型框架结构概念，b) 侧向负载体系和外侧钢柱传力系统 (承重柱)

system at both the office zone and at the residential and hotel zones. The composite option shown in Figure 3 comprise of 135mm trussed deck over composite floor framing. However, option 2 consists of 200 to 250 mm two way reinforced concrete slab with beams. Considering the height of the building and wind conditions, option 2 was selected for the final design as it is more economical, less sensitive to wind effects and its impact on work efficiency, constructability, and overall delivery schedule. Figure 3 also provides the concrete strength, column sizes and core wall thicknesses throughout the building height for option 2. The exterior steel columns in the office zone, between the mega interior columns, are transferred at level 5 to allow for column free lobby. The configuration of the column transfer system at and above level 5 are shown in Figure 2.

390mm two way hollow core (bubble deck) system was also considered as it provided flat ceiling as shown in Figure 4. This option required placing solid concrete beam along the mega column sizes for bracing and stability requirements.

Detailed finite element analysis model for the floor framing system was performed to validate the reinforced concrete floor framing system described above that took into construction sequence, cracking, long term and short term deformation. Figure 5 provides summary of the loading criteria, strength of concrete and the expected slab deflection for the different concrete framing options.

Wind Engineering Approach

The initial architectural design features of the tower and its airfoil shape when combined with very sharp edges are not suitable for a 600m tall and slender tower with 9:1 aspect ratio. The principal author requested collaboration from John Portman and Associates (JPA), principal designers, to modify the design by considering edge treatment and shape variation along the building height by introducing corner slots with varying shapes and sizes, which was later optimized with RWDI for optimum performance. See Figure 6 for the original design concept and history of the architectural design modification for aerodynamic shaping and corner slot treatment. Initial wind tunnel studies revealed that the tower 1) original design concept, with no slots, exhibited excessive accelerations and wind forces that resulted in significant impact on the overall space efficiency and excessive construction cost, 2) overall response is sensitive to the shape and size of slots along the building height, and 3) is extremely sensitive to corner slot shape, size, and orientation. After extensive studies, the final design of the tower resulted in 40% reduction in wind forces and overall dynamic response of the tower. The maximum expected acceleration at the highest occupied floor for both one and ten year return periods were 14.9 and 29.9 milli-g's respectively, thus requiring a damping system at the top of the building.

Because of the split and slender shape of the building, the overall response of the tower needed to be combined with each of the tower legs above the last bridges, thus complicating the prediction of the tower response for each leg. During the development of the tower design, extensive wind tunnel testing force balance testing regimes were considered. However, the additional test needed to conclude the wind tunnel testing programs and selection of the damping would include: aero elastic model studies, pedestrian wind studies, cladding wind load study (including pressure integration), auxiliary damping system selection and studies, and falling ice and snow studies.

The wind climate studies include a statistical analysis of local wind conditions based on measurements from the Inchon Meteorological Station with due consideration to the influence of typhoons based on

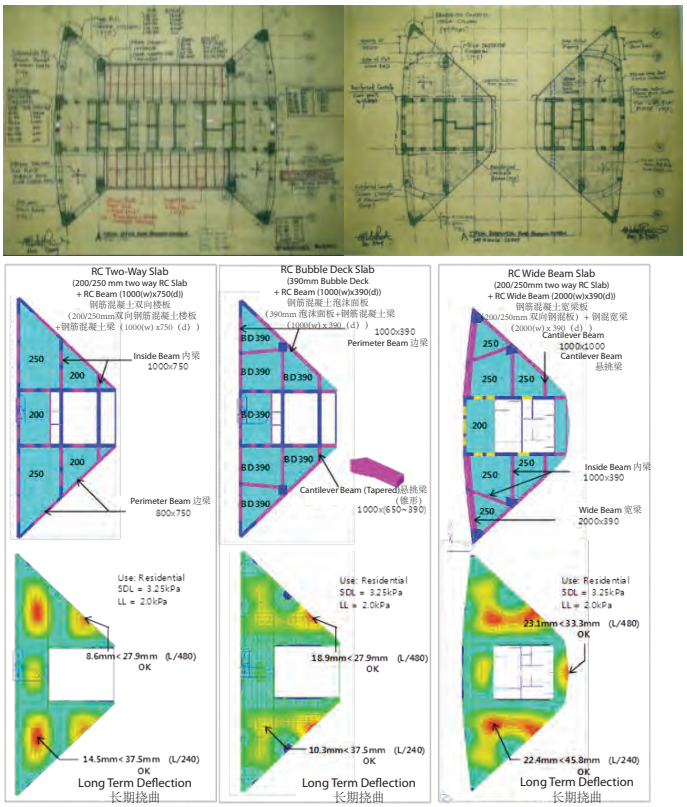


Figure 5. Summary of Concrete Floor Framing Concepts and corresponding Behavior
图5: 混凝土楼板框架结构和对应受力情况对照

的大致情况。此外，巨构的概念还有一个阻尼体系作为补充，来协调塔楼在使用荷载和极限荷载下的动力变化，提供可靠的缓冲(见图10)。

楼层框架体系

塔楼的楼板体系我们考虑了数个选择，但考虑到时间和预算我们最后对两个方案进行了仔细的研究，如图3、图4所示。方案1在办公层和公寓酒店层使用过的是复合楼板体系，图3中所示的复合体系是由复合楼面板和135毫米厚的钢筋层构成。而方案2是由200-250毫米厚、双向配筋的钢筋混泥土板以及梁构成。考虑到建筑的高度和风环境，我们最后选择了更为经济，更能够抵御风荷载的影响，对于工作效率更有利，施工可行性更高以及运输更容易的方案2。图3进一步展示了方案2在不同楼层的混凝土强度，柱子尺寸，核心筒厚度。办公室室内巨柱之间的钢柱在第5层进行了转换，以便在楼下能够有一个无阻碍的大堂，具体的柱网转换系统请参看图2.

390毫米厚的双向空心(中空楼板)结构我们也考虑过，如图4所示，它能够提供一个平整的楼板。但这个方案要求沿着巨柱上布置实心混凝土梁来支撑和稳定。

我们建立了更为详细的楼板体系模型来分析上面所提到的钢筋混凝土楼板的建造程序，长期和短期变形等方面。图5可以看到荷载分布情况，混凝土强度，以及不同方案的楼板估算挠度。

风力应对策略

塔楼最初的建筑设计以及有尖角的翼状平面并不适合这样一个高达600m并且高宽比有9:1之高的纤细高楼。根据主创公司约翰·波特曼建筑师事务所的要求，我们要通过边角切削以及引入不同形

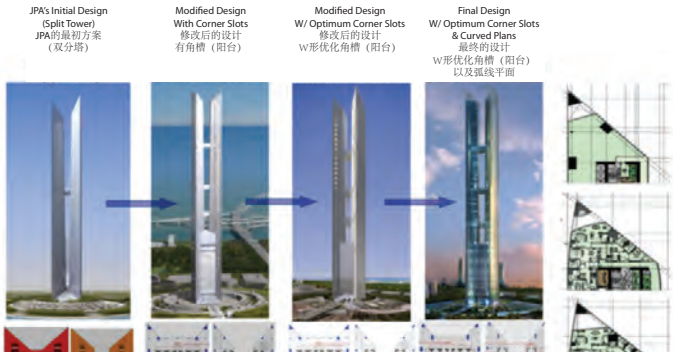


Figure 6. Architectural Massing History for Aerodynamic Shaping with Corner Slot Shaping
图6: 建筑空气动力学塑性和边角切削

a Monte-Carlo simulation for the area. Deriving the wind loads for the Tower were based on 2005 Korean Building Code and Standards (KBCS 2005) with 30m/sec (basic wind speed) x 1.1 (importance factor), which resulted in 33m/sec design wind speed. Performance based design was also considered for wind loads and included the following criteria:

- Deflection: 50 yr wind loads, damping = 1.5%, I = 1.0
- Accelerations: 1yr and 10 yr predictions at 1.0% and 1.5% damping
- Strength: 100 yr wind loads, damping = 2.0%, I = 1.0
- Strength: 300 yr wind loads, damping = 2.5%, I = 1.0
- Strength: 1772 yr wind loads, damping = 5.0%, I = 1.0

In addition to the wind design criteria established above, the wind loads were calculated using the KBCS 2005 using exposures C and D. Comparison of wind loads, story shears and overturning moments are shown in Figure 7. Note that the wind loads per wind tunnel testing program were significantly higher than those predicted by the code. The design of the tower for strength used the worst case conditions. Rational wind loads for 1, 10 and 50 year with different damping were used as a base for 1) predicting the building displacement under different load conditions and their combinations and 2) predicting the maximum building resultant accelerations and torsional velocities. Taming the dynamic response of the tower under wind excitation for both frequent and rare wind events was very challenging as they have to be done within the constraint of the architectural design parameters. However, supplementing the tower with reliable damping system will no doubt tune the dynamic excitation and reduce significantly the design wind forces. Due to the limitation of the paper size, the wind engineering works cannot be fully covered here.

Seismic Engineering

The 151 Inchon Tower is located in Seismic Zone 1 according to the Korean Building Code (KBCS2008) and with 1) Seismic Acceleration Parameter = S = 0.22, 2) Sit classification = Sd (Stiff Soil), 3) Design spectral acceleration (Seismic Design Category D): SDS=0.425; SD1=0.246, 4) Occupancy Category = IE = 1.2, 5) Response Modification Coefficients = R = 5.5, 6) Periodic Parameter (Factored design Seismic Force) = CT= 0.049, and 7) Minimum Design base Shear =Csmin = 0.01. Considering that the dynamic characteristics of the tower (long period) and the fact that the tower is founded on reclaimed land with approximately 20 meter of soft to firm marine silty clay and in close proximity to Japan with high and severe seismic activities, a site specific seismic hazard analysis was commissioned that takes into account the regional tectonic environment, historic seismicity of the region, effect of near and rare, but far earthquake.

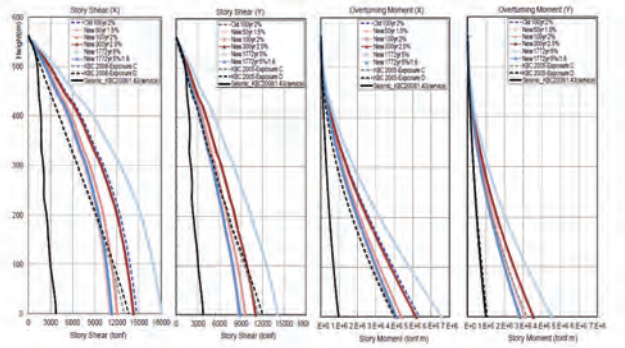


Figure 7. Summary of Story Shear and Overturning Moment along the building height
图7: 沿着建筑高度方向的层间剪力和倾覆临界点

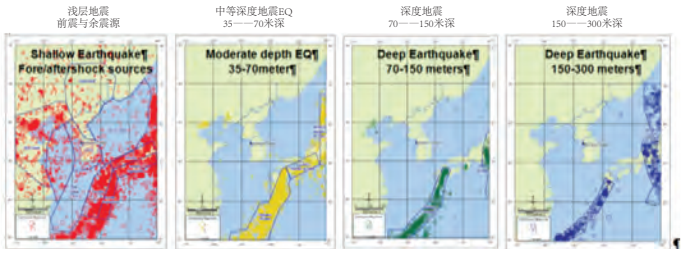


Figure 8. Historic Earthquakes near the Korea Peninsula
图8: 朝鲜半岛附近的地震记录

状大小边角开洞，带来塔楼竖向变化来改进设计，并用RWDI进行优化设计。图6是建筑设计的最初形态和后续通过空气动力学塑性和边角开洞来优化设计的过程。通过风洞实验可以得知塔楼: 1) 也就是最初的设计，没有任何开洞，风的加速效应非常严重，对于空间利用效率以及工程造价有很大的不利影响; 2) 整体性能受沿建筑高度开洞的形状和尺寸的影响较大; 3) 对于边角小的开洞形状、大小、朝向非常敏感，通过大量研究之后，建筑最终设计能够减少建筑40%的风荷载并显著减小塔楼的风振。最顶层的加速度在一年和十年的计算周期里可达到14.9和29.9 milli-g's，因此需要在建筑的顶部设置一个阻尼系统。(见图6)

因为建筑纤细的比例以及一分为二的形态，塔楼的整体效应需要考虑到最高天桥上面分叉的两段，这样就给单边塔楼的受力估算带来了很大的复杂性。在塔楼形状设计演变中，进行大量不同类型的风洞实验。然而，风洞实验和阻尼系统的选择中还需要进行一些其他的测试: 空气动力学模型研究，人行高度风环境研究，外表皮风荷载研究 (包括压力叠加)，辅助阻尼系统的选择和研究，以及冰雪荷载的研究 。

风力气候的研究是基于仁川气象站给出的测量值所做的当地风环境数据分析，并考虑到台风的影响，通过对本地区进行蒙特卡洛模拟而得出的。塔楼的风荷载是基于2005年《韩国建筑规范与标准》 (KBCS2005) 30m/s (基本风速) 乘以1.1 (放大系数)，得出了33m/s的设计风速。性能设计也考虑到了风力荷载，包括以下一些标准值

- 挠度: 50年重现期，阻尼=1.5%，I=1.0
- 加速: 1年和10年重现期，阻尼分别为1.0%和1.5%
- 刚度: 100年重现期，阻尼=2.0%，I=1.0
- 刚度: 300年重现期，阻尼=2.5%，I=1.0
- 刚度: 1772年重现期，阻尼=5.0%，I=1.0

除去以上的风力设计标准，风荷载还用KBCS2005外表面C和外表面D的规范进行了验算。图7是风荷载，层间剪力，和倾覆临界点的比较。值得注意的是，每次风洞测试时所加的风荷载都远远大于规范所要求的。塔楼刚度是按照最差环境情况来设计的。考虑1年，10年，50年重复周期的风荷载以及不同的阻尼值能够: 1)

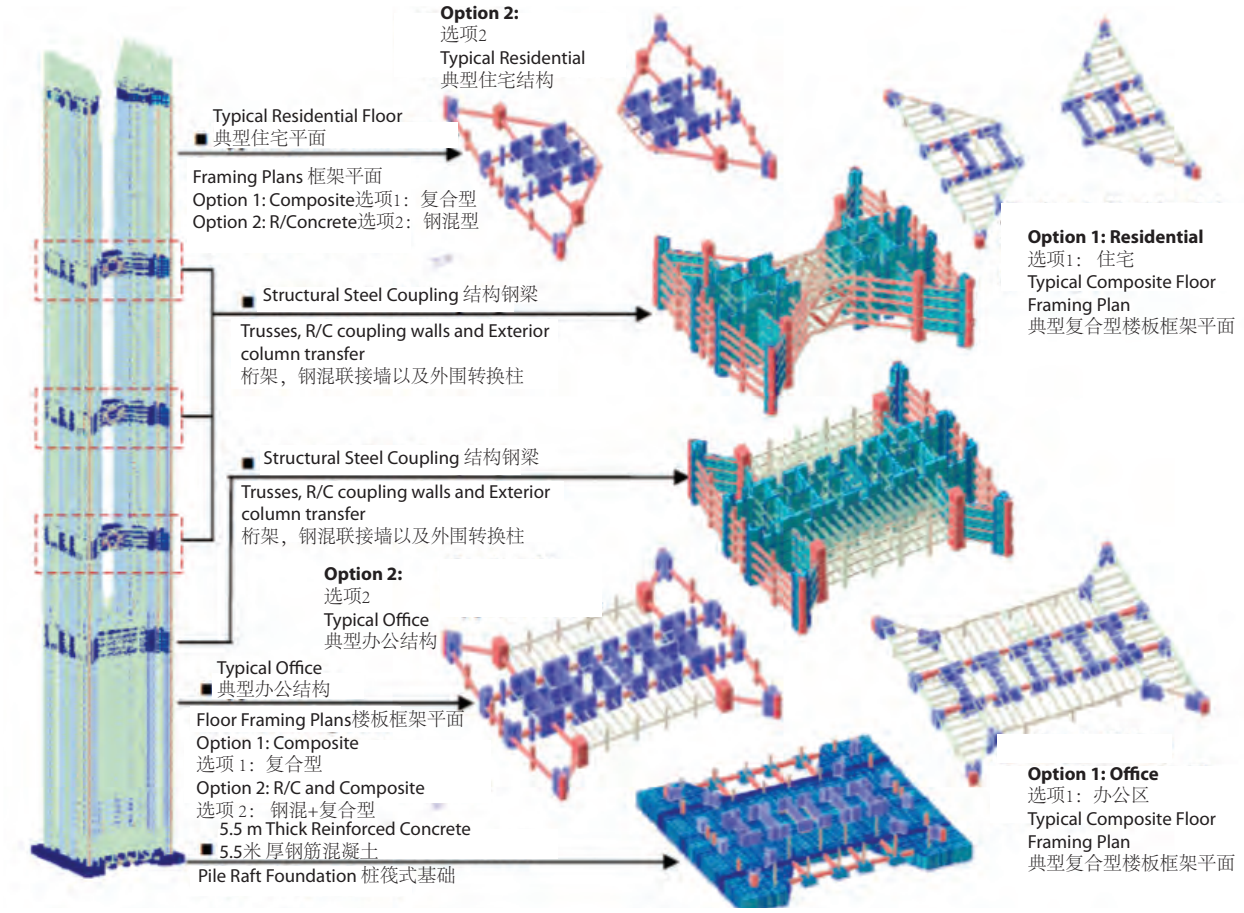


Figure 9. Structural System Summary for option 1 & option 2 and their Corresponding three (3) Dimensional Finite
图9: 方案1，2的结构体系对比，以及它们应对不同荷载的形变模型，形变周期和体量形变率

Site specific response spectrum curves and time history records were provided for frequent and rare seismic events. Figure 8 depicts some of the historic earthquakes, near the Korea Peninsula, that were used for determining the site specific seismicity. Because of the tower long period, the lateral load resisting system of the tower is controlled by wind forces.

Verification of the Lateral Load Resisting System

Detailed three-Dimensional Finite Analysis Models (FEAM) for both the composite framing, option 1, and for the concrete framing, option 2, were prepared that included the floor framing arrangement described above, exterior column transfer systems, raft foundation, and the pile foundation flexibility, and the P-delta effects. The complete soil structure analysis models as shown in Figure 9. The analysis was also used to simulate the construction sequence of the tower and its impact on the design of the multi-story outrigger/shear panels.

The analysis also includes a detailed analysis of the soil-structure interaction, where the raft foundation and pile stiffness are modeled in detail to expedite the system studies comprehensively. Because the tower piles are founded in more than 20 meters of soft marine silty clay, the tower's lateral movement and dynamic behavior are sensitive the soil subgrade modulus. Therefore, extensive studies and pile testing regimes were put in place by the principal author to ensure the overall response and behavior of the tower under extreme loading conditions are captured, especially as it related to selecting appropriate pile stiffness under gravity loads, dynamic wind and seismic loads, dynamic lateral stiffness of the pile, and the mechanism of dissipating the lateral load

估算建筑在不同的荷载条件以及组合情况下的变形，2) 估算建筑最大的总加速度以及扭转速率。在建筑设计限度的制约下，减缓塔楼在频繁以及极端风环境下风荷载造成的风振是件非常具有挑战性的事情。然而，通过在塔楼上补充一个牢靠的阻尼系统不仅能够缓和动力形变，也能显著地减小建筑风荷。鉴于文章篇幅所限，风力工程上的更多细节无法一一介绍了。(如图7)

抗震设计

151层的仁川塔位于《韩国建筑规范2008》所规定的一级震区中: 1) 地震震害指数S=0.22; 2) 地质分级=坚硬土壤; 3) 设计的谱加速度 (抗震类型D)，SDS=0.425，SD1=0.246; 4) 使用率=IE=1.2; 5)结果修正系数=R=5.5; 6) 周期参数 (地震力参数) =CT=0.049; 7) 地基最小剪力值=Csmin=0.01。考虑到塔楼 (长期) 的动力学特点以及建造在一片填海所得的土地上，有将近20米厚的从软到硬的滨海淤泥层，与日本相似深受剧烈地震活动的影响，因此不得不进行基地的地震灾害分析，包括该地区的地质环境构造，地区地震历史，周边以及过往地震的影响。

我们找到了基地对于频繁性和罕有的地震活动的特定回应谱线和历史记录。图8显示了在朝鲜半岛附近的地震历史，用来决定基地所需的抗震级数。因为塔楼较长的结构重现期，侧向荷载受力系统是由风荷载来决定的。

侧向荷载受力系统的测试

基于方案1复合框架结构和方案2混凝土框架结构各自的3D分析模型 (FEAM) 已经建立好，包括了楼板框架结构，外部柱子的传力体

to the foundation. The tower lateral displacements and inter-story drifts were limited to H/500 and H/350 for 50 year return period respectively. The results of the dynamic frequency analyses are depicted in Figure 9.

Supplemental Damping System for the Tower

Extensive wind engineering studies and wind engineering treatment were considered to control the dynamic excitation of the tower under frequent and severe wind events. However, working within the limitation of the design concept, the dynamic response for the building was reasonably controlled, but could not meet the habitability and service requirements for this high-end residential tower. Thus, a supplemental damping system was considered for the tower. Considering the latest technological advances in damping devices, the author suggested the toggle damping system at the structural steel coupling trusses as shown in Figure 10. The intent of this damping system is to provide a reliable damping system to control vibration induced by wind and seismic excitations for both serviceability and ultimate loading conditions. See Figure 10 for preliminary selection of the toggle frame geometry brace geometry and configuration.

Detailed and extensive numerical analyses were performed to test the efficacy of the mega-toggled brace system geometry and configurations. The numerical results demonstrated that mega-toggle brace system provided substantial increases in damping and reduction in the dynamic response of the building. The preliminary analysis results also showed that this type of viscous damper can be applied to control low and high level of dynamic input. The principal author believes that integrating a reliable damping system in the fundamental design concept of building structure must be considered to continue to improve the reliability of building structure for sustainable cities that must work under extreme events. The principal author believes that integrating supplemental damping system into supertall building structural design will provide a catalyst for new generation of tall building systems.

Foundation System: Pile Supported Pile Raft Foundation

The tower superstructure is founded on 5.5 meter thick, high performance reinforced concrete raft foundation over 172-2.5m diameter reinforced concrete piles. The piles are designed for 6000M Tonnes service capacity and are intended to anchor into competent soft rock at least 5 meters. The final pile lengths vary significantly, from 45 to 76 meters, because of the variability of the geotechnical weathered and soft rock formation. The selection of the final pile toe location was also influenced by the presence rock fractures in the soft rock formation.

Selection of the optimum pile size, number of piles, and pile layout were determined from a series of trial analyses undertaken collaboratively by the geotechnical designers and the structural designers. To evaluate the foundation settlement, the geotechnical engineering consultants used Plaxis 3D and other relevant programs. Based on these analyses, the pile stiffness values were provided and used to finalize the foundation design. An independent 3-dimenational finite element analysis, using general analysis programs (MIDAS and ETABS), was also performed to include the soil structure interaction and the stiffening effects of the superstructure. This analysis also included the construction sequence of the tower to allow for additional load redistribution between the piles because of the large stiffness of the superstructure. Figure 11 shows the 5.5 meter raft foundation geometry superimposed over the pile

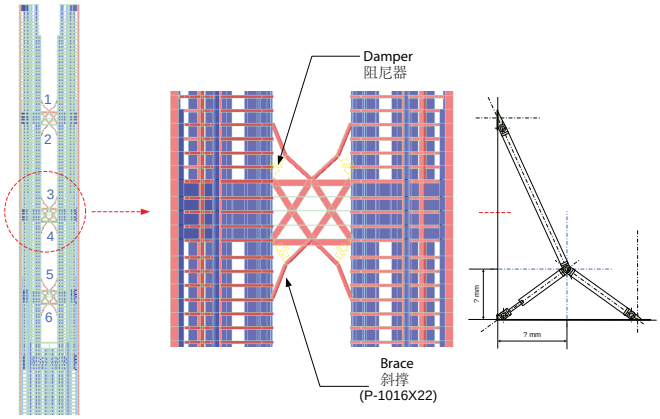


Figure 10. Mega -Toggle Brace Damper, A new generation for Tall Building System
图10: 巨型套索支柱阻尼器，高层建筑体系的新纪元

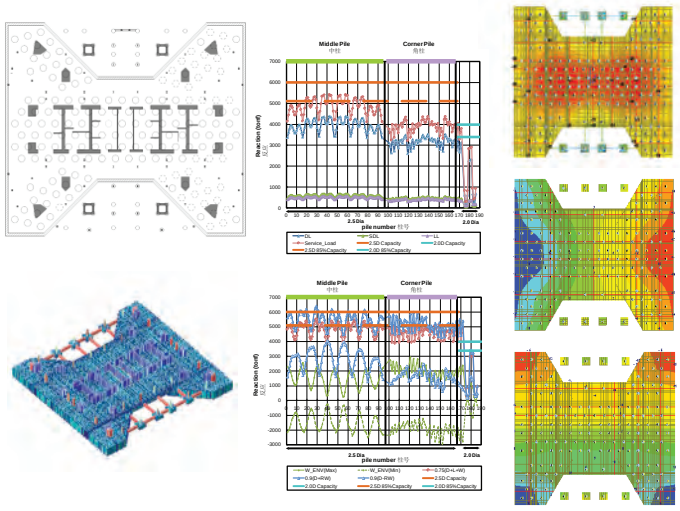


Figure 11. Raft Foundation Plan superimposed over Pile Layout, and results of the Foundation Analysis.
图11: 筏形基础叠加在桩基之上，基础受力分析结果

系，筏形基础，桩基的灵活性以及P-三角效应。图9展示了完整的建筑结构分析模型。这个分析也能够用于模拟塔楼的建筑施工顺序以及对于多层悬挑/剪力墙结构的影响。

这个分析也包含了对于地基-结构结合部分的进一步研究，对筏形基础和桩基强度更为仔细的考量，以便能继续对系统进行更全面的研究。因为塔楼的桩基打入的是20余米深的海滨淤泥地，塔楼的侧向位移和动力学状态受地基的影响很大。因此，我们进行了大量的研究和桩基测试，保证涵盖到塔楼在各种极端荷载情况下的应变和状态，尤其考虑了对于重力荷载、风荷载、地震荷载下的桩基刚度选择，桩基的侧向动力刚度的选择，以及将侧向荷载转移到地基中的机械设备的选择。塔楼的侧向变形以及层间偏移在50年的重复周期下分别被控制到了H/500和H/350。对于动量频率的研究结果请参考图9。

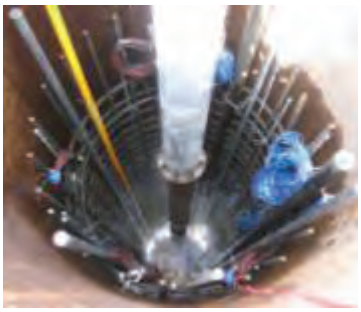
塔楼的补充阻尼系统

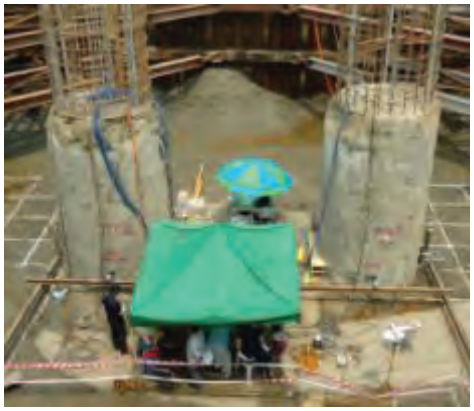
我们进行大量的风环境研究和改善策略来控制塔楼在常规和极端风环境下的动力应变。然而，基于建筑的极限设计值，建筑的动力应变得到的控制，但作为一个高端的公寓楼来说，宜居程度和设施配备都没有达到相应的要求。因此，我们选取了阻尼系统来对塔楼进行补充优化。比较了现今最先进的阻尼系统，笔者选择在图10所示的结构性钢桁架上增加了一个套索阻尼系统。这个系统的目的是为建筑提供了一个可靠的阻尼缓冲，减小建筑在风荷载和地震荷载下的形变，从而保证可用性和荷载承受能力。

layout, the raft foundation detailed analysis model, and a summary of the foundation analysis results, including foundation settlement, behavior of the foundation under wind loads, the pile axial load distribution summary. Note that 1) the final pile layout is optimized and result in equal load conditions under gravity and lateral loads, 2) the maximum tower predicted settlement and differential settlement are 42mm and 20mm respectively, and 3) the expected foundation behavior is linear under lateral loads.

我们做了大量深入的研究来确定这个巨型套索支柱阻尼器的几何形态和构件。无数个测试结果都佐证了巨型套索支柱系统能够明显的提高阻尼，减小建筑的振幅。初期的分析结果也表明这种粘性阻尼器能够用于控制低动能情况，也适用于高动能的情况。笔者认为，未来的城市强调可持续发展并能应对各种极端天气情况，在建筑结构设计的基础阶段就能考虑将阻尼系统整合进去会是优化建筑结构的一条可靠途径。笔者坚信在超高层建筑中整合阻尼体统会成为未来高层新纪元的一个催化剂。





Test Type 受力种类	Purpose 预测	Loading Method 施力方式	Monitoring Items 监测变量
Vertical 垂直 (4 No. test piles) (4个桩基测试)	Estimation of the end bearing and shaft friction capacities within weathered/ soft rock 测试断点受力和螺纹钢与风化岩或软性岩的摩擦力 Evaluation of the vertical pile stiffness 竖向桩基的强度 Check of pile response and stiffness to due to static and dynamic/repetitive/ cyclic loading such as wind and seismic loads 测试桩基对于静态的/动态的/重复的/周期的荷载比如风和地震的回应和刚度	Bi-directional load cells (O-cells) embedded at two locations in pile (1 in upper shaft and 1 close to pile toe) 多向的施力构件 (构件O) 被安装在桩基的两个位置 (一个在上端一个在下端)	Pile movement of shaft and toe 桩基上端和下端的位移 Stress, strain along piles 沿着桩基的压力和拉力 Pile stiffness under repetitive/cyclic loading due to wind and seismic loads 桩基对于重复的/周期的荷载比如风和地震的回应和刚度
Horizontal 水平 (1 No. test & 1 No. reaction pile) (1个测试和1个回应桩基)	Evaluation of the lateral pile stiffness Lateral deformation characteristics of UMD around pile head 测试侧向桩基的刚度，桩基顶部UMD的侧向的变形情况 Check of pile response and stiffens due to static and dynamic/repetitive/cyclic to loading such as wind and seismic load 测试桩基对于静态的/动态的/重复的/周期的荷载比如风和地震的回应和刚度	Loading of the test pile against a reaction pile (static & dynamic loading) 将测试桩基和一个受力 (静态&动态荷载) 桩基绑定	Lateral load and displacement 侧向荷载以及变形 Pile deflections along the shaft 桩基沿筏形基础的偏移 Pile stiffness under cyclic/repetitive loading. 桩基在重复/周期的荷载下的刚度

Figure 12. a - e) O-Cell Pile Vertical Load Test and instrumentations, f) Lateral Load Test, g) Load Test Programs
图12: a-e) 构件O桩基垂直荷载测试，f) 侧向荷载测试，g) 测试项目

During the main design stage, the pile design was generally based on theoretical solutions and previous experience in similar conditions at adjacent sites. However, because of the complexity of the 151 Inchon tower, a detailed pile load testing program was put in place to confirm the design assumptions and finessing the foundation design. The piles were instrumented so that detailed information could be derived on the distributions of shaft friction and soil stiffness at various depths along the pile shaft. The following comprehensive vertical, lateral, and cyclic pile load testing program was developed for the tower foundation piles, as shown in Figure 12, to achieve the following objectives:

- Assess and confirm the constructability and integrity of the piles using the proposed construction techniques (reverse circulation drilled piling techniques).
- Allow comparison of measured pile performance with design expectations and refinement of the geotechnical parameters adopted in design (e.g. ultimate skin friction and end bearing values, pile foundation stiffness, effect of dynamic loading on the pile stiffness, both vertical and lateral, etc.).
- Assess possible variability of pile performance in relation to variations in ground conditions across the foundation footprint.

The pile load test shown in Figure 12 shows the vertical and lateral pile load arrangement and instrumentation. The vertical load test was carried to ultimate load with overall safety factor greater than 3. The lateral load test was also subject to dynamic load test to confirm the lateral soil stiffness under dynamic loads. The results of the pile testing program and regimes were covered in separate papers and has detailed descriptions of the geotechnical engineering works performed for the 151 Inchon Tower and cannot be covered here.

地基系统: 筏形桩基

塔楼整个巨型体量落在由5.5米厚高强度钢筋混凝土的筏形地基上，筏形基础打入地下的桩基共172根，内径2.5米。这些桩基的设计荷载值是60亿吨，最少打入地下有承载力的软石层5米以上。最终桩基的深度各异，由于地理工程学上不同的风化和软性地基从45米到76米不等。最终桩基的打入地下的位置也考虑了现今岩石断层和软性石基的构造。

桩基形状的优化选择，桩基数目，以及打桩位置是由一系列地理工程师和结构设计师共同分析实验后决定的。为了评价基地设计，地理工程咨询师运用了Plaxis 3D和其他的软件。基于这些分析，确定了桩基的强度从而确定了最终的方案。用常用的软件 (MIDAS和ETABS) 也进行独立的三维定量分析来确定地基和结构的相互作用以及这个超级结构系统的硬化效应。这个研究也包括了塔楼的施工顺序分析，从而能够根据结构的硬化重新分配桩基的荷载承受量。图11展现了在桩基上叠加的5.5米厚的筏形基础，筏形基础的详细分析模型，以及地基分析结果的概括，包括了基础方案，风荷载下基础的变化，桩基轴向受力分配。注意，1) 最终的桩基分布是基于重力荷载和侧向荷载相同的情况下最优解，2) 地基下陷的最大估算值和差值分别为42毫米和20毫米，
3) 地基在侧向荷载下的预想变形是线性的 (如图11) 。

在主要设计进程中，桩基是设计主要是依据现有理论和附近相似基地条件下的工程经验。然而，由于仁川塔151层的高度带来的复杂性，我们对于设计推想进行了一个实地详细的桩基负载实验，完善了最终的地基设计。桩基上都安装了测量仪以便能够获得桩基不同高度的构件摩擦力和土壤刚度值。后续对塔楼基础桩竖向、侧向和径向的荷载都进行了测量 (见图12) ，从而达到以下目标:

- 对用规划的建造技术打的桩基造价和施工难易度以及整合性进行评估 (不使用通常的钻头打桩技术)
- 提供一个桩基性能测量值与设计预期值的对比，以及对于设计中运用到的地理技术参数的优化。(比如表面摩擦极限值，端头荷载极值，桩基强度，垂直或侧向动荷载对于桩基强度的影响，等等)
- 获知基地范围内土地条件的差异能够导致的桩基性能差值。

通过图12中的桩基荷载测试，我们能够得知桩基竖向和侧向荷载的分布和影响。竖向荷载的最大值是规范安全值所要求的3倍。侧向上还进行了动态荷载的实验来验证侧向土壤的强度。关于桩基的测试项目和结果还有另一篇论文，对于151层的仁川塔的地理工程技术有着更为详尽的介绍，本文就不再赘述。

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