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The Signature Tower: Reaching High in the Sky of Indonesia

Signature大厦：印度尼西亚最高塔

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Abstract

The anticipated fifth tallest building in the world will be reaching high before 2020 in the sky of Indonesia, one of the most active seismic zones in the world. With its top crown, the tower will reach 638 meters. The total area of its 111 floors, including 6 basement levels, is 550,000 m^2. Since it stands on very deep, soft soil layers of alluvial deposit, the tower has a complex seismic behavior. Furthermore, it is very slender with some architectural setbacks at its corners. This paper discusses the reasons behind the selection of the structural systems, as well as the use of advanced structural analyses and design methods, including the Performance-Based Design, which considers the risk-targeted MCE levels of seismic hazard. The site, as a part the SCBD super block, is also going to be discussed with the urban design guidelines imposed on it.

Keywords: Seismic Zone, Alluvial Deposit, Slender, Performance Based Design, Urban Design

摘要

即将位列世界第5高的标志(Signature)大厦将于2020 年前，在世界上最活跃的地震带之一的印度尼西亚建成。大厦包括塔冠高度将达到638米。其111层包括6层地下室，总面积达550,000平方米。由于塔楼耸立于较厚的冲积软土地层，因此保证塔楼具有良好的抗震性能十分重要。此外，塔楼的长细比较大，并且在其角部还有一些建筑形态上的收缩。本文讨论了如何选择结构体系，以及采用先进的结构分析和设计方法，包括考虑地震灾害MCE风险目标的性能化设计方法。作为ＳＣＢＤ商务区项目群的一部分，与该项目开发有关的城市规划理念也将在本文中讨论。

关键词：地震带、冲积层、柔度、性能化设计、城市规划

Overview

Indonesia has enjoyed steady economic growth since the early 2000s. Along with economic growth, there has also been an improvement in infrastructure development, notably the plan to build mass rapid transit (MRT) systems. Jakarta is the capital and most populated city in Indonesia with almost 10 million people (12,000 people/km^2 density). Jakarta Metropolitan area consists of 4 other satellite cities, with each city having a population between 1-1.5 million. The development of Jakarta in the past 40 years has tended to be horizontal and sprawling into rural areas. The need to have higher density development is crucial. The burden of the city's infrastructure is enormous, with traffic congestion, waste and water management. More concentrated and higher density development will partly resolve the city's problems.

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综述

印度尼西亚经济自2000起就呈稳定增长态势。随其经济的增长，基础设施也不断地改善，尤其是快速交通运输系统（MRT）的建设。雅加达是首都也是印尼人口最多的城市，接近1千万人（人口密度为每平方公里1.2万人）。雅加达市区包含有4个卫星城，每个卫星城人口在100到150万之间。雅加达的发展在过去的40年中趋于平稳，并开始向郊区发展。高密集化的发展需求已迫在眉睫。交通堵塞、水资源管理和浪费，加重了城市基础设施的负担。因此更加集中和高密度化的开发将会在一定程度上解决这些城市问题。

标志大厦的建造就是以满足这些需求为目标的。它座落在雅加达Sudirman中央商务区，具有绝佳的战略性地理位置。作为交通枢纽，该地区拥有多种交通体系，并与2个规划中的快速运输系统相邻。早在1992年，该地区就计划建造88层高的高层(见图1)。该区现已成为雅加达一个最具发展前景的地块。业主决定在此建造雅加达最高楼 （2020年将成为世界第五高建筑——数据来自CTBUH)。

这座111层高的标志大厦方案是由Smallwood, Reynolds, Stewart, Stewart建筑师事务所设计，由集商业、会议和休闲于一体的裙房，三个办公区，酒店及观光层组成。裙房以下是6层地下室，主要

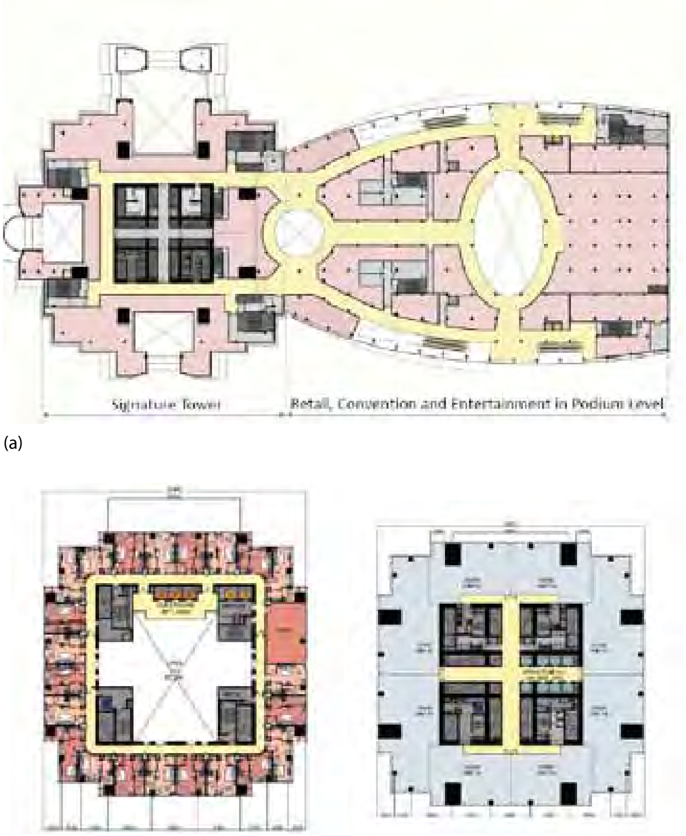
Figure 1. Sudirman CBD Plan 1992 with 88-storeys Tower (Source: Center of Urban Design Studies – PSUD)
图1. Sudirman中央商务区1992年规划建筑88层塔楼（出自：城市设计研究中心PSUD）

Figure 2. Bird's-eye view of Signature Tower (Courtesy SRSSA)
图2. 标志大厦鸟瞰图（出自： Courtesy SRSSA）

Jakarta Metropolitan area consists of 4 other satellite cities, with each city having a population between 1-1.5 million. The development of Jakarta in the past 40 years has tended to be horizontal and sprawling into rural areas. The need to have higher density development is crucial. The burden of the city's infrastructure is enormous, with traffic congestion, waste and water management. More concentrated and higher density development will partly resolve the city's problems.

The Signature Tower is planned to accommodate those needs. It is strategically located in the central business district of Jakarta, the Sudirman Central Business District (SCBD). The location is accessible by multi-modes of transportation. It is also adjacent to two of the planned MRT stations. The original plan was a 88-storey high rise building in 1992 (see Figure 1). The area has become one of the best developments in Jakarta. The land owner then decided to build the tallest tower in Jakarta (5th tallest in the world in 2020 – data from CTBUH).

This 111-storey Signature Tower scheme was developed by Smallwood, Reynolds, Stewart, Stewart and Associates to include retail, convention and entertainment in the podium level, three zones of office, hotel and observation level. Below the podium level are 6 floors of basement, which are used mainly for mechanical room, back of house and parking space. The total area of the development is approximately 550,000 m2 (see Figure 2 and Figure 3).



(a)

(b)

Figure 3. (a) Level 6 floor plan; (b) Typical office and hotel floor plans (Courtesy SRSSA)
图3. （a)六层平面图，（b)标准的办公和酒店楼层平面图（出自：Courtesy SRSSA）

布置为设备区、储物间和停车场。总建筑面积约550,000平方米（ 见图2和图3）。

场地条件

作为一个50公顷SCBD项目的一部分，该地块的开发需要符合有关城市规划的要求。Signature塔楼位于第6和第7地块，未来将会扩展到第8地块（见图4）。该地块用于建造地标性建筑。第6和第7地块的总面积为32,149平方米，三个地块的总面积为50,674平方米。该地块位于雅加达南北和东西轴心交汇处，与主要道路入口相连，并与Semanggi交通枢纽相邻。位于雅加达的金三角地带(参见图5)，在这里集中了很多重大的工程项目。场地北面的“Gelora Bung Karno” 是占地400公顷的国家体育综合设施，多用于体育和娱乐活动场所。该地块与未来雅加达快速运输系统和其他公共交通设施相连，整个场地较为平坦。沿标志大厦场地南北向有隧道与之相连。

地质条件

首都雅加达位于雅加达盆地。众所周知，这个盆地主要是冲积层，是由可压缩粘土、成型不久的砂和砾石以及高风化凝灰质泥沙火山岩组成。要满足这个项目的要求，需要通过细致的200米深野外勘探来确定地下的地质条件。要进行标准贯入试验(SPT)、圆锥贯入试验(CPT)、压力仪(PMT)测试；要采用原状土样进行特性指标、压缩模量、剪切强度的实验室试验；并通过井下地震测试 (SDT) 确定场地剪力波速度分布。此外，还要通过抽水井和几个观测井进行地下水监测和抽水试验，为开挖总深度达23.5米的6层地下室防水设计提供依据。

土壤勘探表明场地地下含6个土层，主要为：8米厚的软弱到中硬度的粘土，5米厚的中硬度硬粘土，在20米厚的硬淤泥和密度非

Site Condition

As part of a 50 hectares SCBD development, an urban design guideline for the area is applied to the development. The Signature Tower is located in Lot 6 and 7 with future extension to Lot 8 (see Figure 4). The site is designated as the landmark tower area. The total area of Lot 6 and 7 is 32,149 m^2. The total area for the three lots is 50,674 m^2. The site is connected to the major road access; north-south and west-east axis of Jakarta, adjacent to the Semanggi interchange. It is located within the golden triangle area of Jakarta, where all the major development is located (see Figure 5). North of the site is "Gelora Bung Karno" national sports complex that consists of 400 hectares of land, mostly for sport and recreational activities. It is connected to the future Jakarta MRT and other public transportation. The site is relatively flat. It also has a tunnel connection through the site, on the north and south part of the Signature Tower site.

Geological Condition

The capital city Jakarta is located in the Jakarta basin. It is known that this basin is mostly dominated by alluvial deposits which consist of relatively compressible clay, sand and gravels associated with young, highly weathered volcanic rock of tuffaceous clay and sand. For the purpose of this project, the geological subsurface condition was identified through detailed field exploration drilling to 200 meters deep. Standard penetration test (SPT), cone-penetration test (CPT), and pressure-meter test (PMT) were conducted. Undisturbed samples were conducted for index properties, compression or modulus, and shear strengths laboratory testing. Seismic downhole test (SDT) was also carried out to identify shear wave velocity profile of the site. In addition, groundwater monitoring and pumping test from pumping wells and several observation wells were also conducted for dewatering design purposes of the six levels of basements with a total depth excavation of 23.5 m.

The soil exploration indicated that the subsurface consists of the following six soil-layers: 8 meters soft to medium stiff clay, 5 meters of medium stiff to stiff clay, 20 meters of hard silt and very dense sand over about 15 meters of very stiff clay. These layers are underlain by about 75 meters of hard clay over 75 meters of hard silt and very dense sand. The average groundwater level is 10 meters below the existing ground surface.

Since the tower weight will be relatively very high and the subsurface layers are considered to be compressible, particularly for the clay layers from 35 – 120 meters depths with average N-SPT values in the range of 30-40, then both comprehensive consolidation and shear-strength tests were needed. Both undrained and drained triaxial tests were required to obtain the corresponding shear strengths. Constant rate of strain consolidation tests were conducted in order to accurately identify pre-consolidation pressure and compression index of the compressible clay layers.

Site-Specific Seismic Design Criteria

Due to many recent large earthquakes in Indonesia, a detailed seismic hazard analysis needs to be conducted to determine seismic design criteria for the tower. These design criteria are based on a new concept that considers both seismic hazard of the site and integrating it with the fragility of the building to derive the so called risk-targeted maximum considered earthquake (MCER). This MCER is defined as a 1% probability of the building collapsing within 50 years.

Figure 4. Sudirman CBD Plan 1992 and the surrounding area (Source: Center of Urban Design Studies – PSUD)
图4. 1992年规划的Sudirman中央商务区及周边地区（出自：城市设计研究中心PSUD）

Figure 5. Sudirman CBD Public Transportation and Access
图5. Sudirman中央商务区公共交通及通道

常大的沙子上面覆盖约15米厚的坚硬粘土层。这些土层的底下是约75米厚的硬粘土，覆盖超过75米厚的坚硬淤泥和高密度沙层。地面以下地下水位平均深度为10米。

塔楼的相对重量非常大，而且地下的土层是可压缩的，尤其是35-120米厚、N-SPT平均值在30-40范围的粘土层，因此需要进行测试饱和固结剪切强度的试验。要用不排水和排水三轴试验来获取相应的剪切强度。为了准确地确定粘土层的预压固结压力和压缩性指标，还需要进行等应变速率固结试验。

小地块抗震设计准则

由于近期在印尼发生了一些较大的地震，因此需要进行一个详尽的地震风险分析来确定塔楼的抗震设计标准。这些设计标准是基于一个新的概念，也就是把场地地震风险和建筑物损坏作为一个整体来考虑，得出风险概率目标最大地震(MCER)。这里把MCER定义为50年内建筑物倒塌概率为1%。 MCER通过计算风险概率总

The MCER is developed by calculation of risk-integral, consisting of hazard curves of maximum considered earthquake (MCE). It is defined as a 2% probability of exceedance (PE) in 50 years resulting from a probabilistic seismic hazard analysis (PSHA) of the site and fragility function of the building. The seismic criteria are also made for Service Level Earthquake (SLE), defined as a 50% PE in 30 years. The seismic design criteria are conducted in conformance with Pacific Earthquake Engineering Research Center (PEER) Tall Building Provisions (2010) and American Society of Civil Engineer (ASCE) 7-10.

Seismicity of the site was investigated through PSHA, considering subduction zones and shallow crustal faults as well as background seismicity within 500 km radius of the site. Seismicity data around the site indicate seismic events that occurred from the year 1900 to date and seismic source zones as presented in Figure 6. Maximum magnitudes and seismic parameters for each seismic source zone are identified. The most recent ground motion predictive equations (GMPE) for each of the subduction, shallow crustals, and background sources are adopted in the PSHA. Results of the PSHA are hazard curves of both level hazards of MCE and SLE at reference subsurface rock, having shear wave velocity (Vs) of 760 m/s (SB). MCE is further integrated with fragility function of the tower to obtain MCER .

Comprehensive analyses through logic-tree formulation and sensitivity analyses on maximum magnitudes of the seismic source zones were performed. De-aggregation analysis has been conducted to identify dominant events corresponding to the levels of probabilities and oscillatory periods of interest near the natural period of the tower. Seismic input motions for both SLE and MCER at reference rock SB were generated. Seismic input motions were generated through spectral matching techniques to target the spectra derived from the de-aggregation analysis.

The seismic input motions were adopted in a non-linear time-domain wave propagation analyses from reference rock (SB) to ground surface. The shear wave velocity profiles were obtained from the combination of seismic down-hole test and ambient noise micro-tremor survey, to characterize the reference subsurface rock to ground surface, to a depth of approximately 500 m. The reference rock SB with shear wave velocity of 760 meter/second was identified at a depth of 300m from the ground surface. Figure 7 shows the shear wave velocity profile from ground surface to 300 m depth. Wave propagation analysis based on the Vs profile and seismic input motions, scaled at various oscillatory periods from 0-10 seconds, have been conducted. The results recommended ground surface Design SLE and Design MCER in the form of response spectra as shown in Figure 8.

Wind Tunnel Test

For super blocks and high-rise buildings of more than 50 floors (200 m height), the Jakarta municipality requires a series of wind tunnel tests to be carried out. For this purpose, a series of wind tunnel tests was conducted at the Rowan Williams Davies & Irwin Inc (RWDI)'s 2.4 m × 2.0 m boundary layer wind tunnel facility in Guelph, Ontario, Canada. Wind tunnel tests were done on a 1:500 scale model, including its proximity surroundings within a 600 m diameter, and measured using a very sensitive High-Frequency Force Balance (HFFB) test. Figure 9 illustrates the wind tunnel test conducted in the laboratory. The wind climate model was scaled so that the magnitude of the wind velocity for the 100 year return period corresponded to a mean hourly wind speed of 40 m/s at gradient height in open terrain. The summary of predicted peak overall structural wind loads is shown in Table 1. The base shear and the overturning moment from the wind tunnel

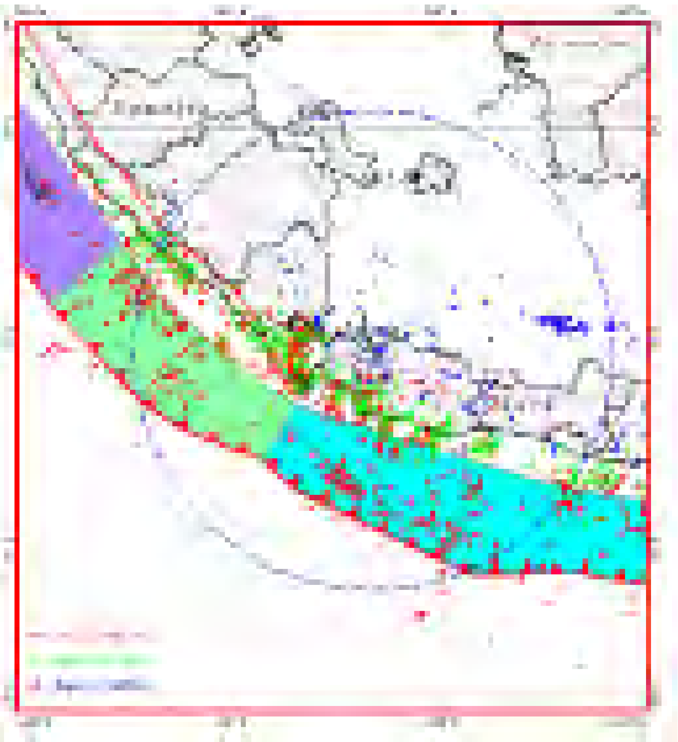


Figure 6. Distribution of main-shocks seismicity data around the tower site
图6. 塔楼场地周边主震震级分布

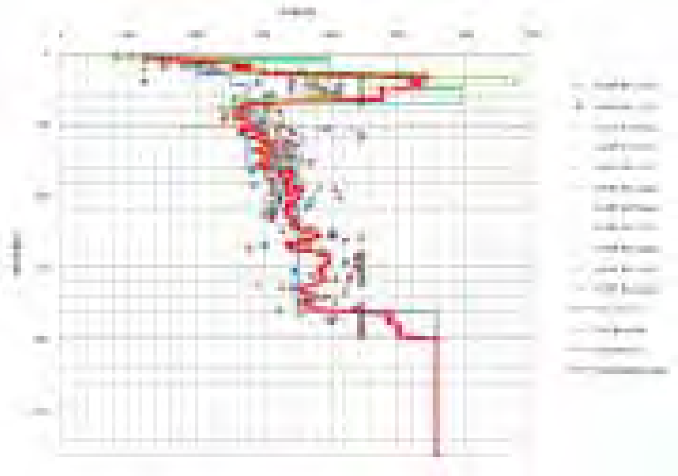


Figure 7. Shear wave velocity (Vs) profile of the site based on seismic downhole test, microtremor test, and N-SPT correlation
图7. 基于地震下孔法测试，微震测试以及N-SPT相关性的剪切波速分布

和得出，该风险概率总合含有最大地震风险概率曲线(MCE)。根据场地和建筑物破坏概率风险分析(PSHA)，把它定义为50年内超越概率为2%(PE)。抗震设计准则也可用于小震设计(SLE)，定义为30年内超越概率为50% 。该抗震设计标准与太平洋地震工程研究中心(PEER)的高层建筑规定(2010)以及美国土木工程师学会(ASCE)7-10一致。

考虑俯冲带、浅层地壳断层以及场地内方圆500公里范围内的背景地震活动性，通过PSHA对场地的地震活动性进行分析。图6中给出了从1900年至今的震源场地地震数据，确定了最大震级和每个震源的地震参数。在PSHA分析中采用了每个俯冲带的最新地面运动预测方程(GMPE)、浅层地壳和背景震源。PSHA分析的结果给出了地表下参考岩面MCE和SLE两种风险水平的风险曲线，其剪切波速(Vs)达760 m / s(Vs)。MCE进一步与塔楼破坏程度相结合就可得到MCER。

设计人员对场地进行了逻辑关系整体分析和震源最大震级敏感性分析。进行参数分解研究确定主要地震，发现其相应的概率水平

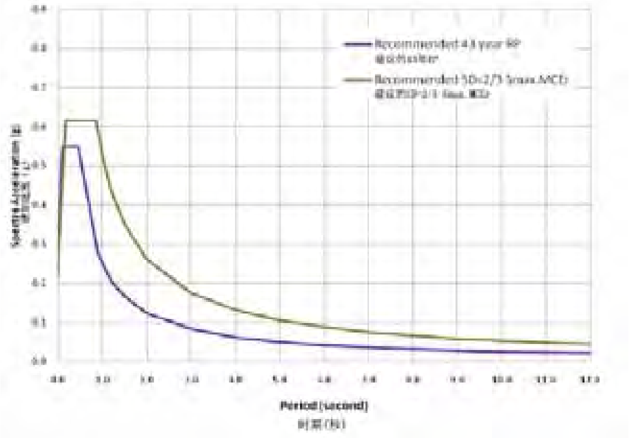


Figure 8. Ground surface response spectra of recommended SLE and SD = 2/3 * SMax MCER resulted from SSRA
图8. 从SSRA得到的建议的SLE和SD=2/3*SMax MCER地表反应谱

analyses are around 46% - 60% and 69% - 80%, respectively, when compared to the seismic load. Therefore, this tower's lateral system is governed by the seismic load.

The predicted peak accelerations for the 1-year return period and the 10-year accelerations with 1% critical damping ratio are 6.0 milli-g and 13 milli-g, respectively. These values are still below the 1-year return period International Organization for Standardization (ISO) limit value for office and residential buildings and the 10-year acceleration limit under the RWDI's criteria for an office tower and residential building, respectively. Therefore, the predicted accelerations are acceptable for human comfort in an office building. The wind tunnel tests were also used to measure the cladding wind load, stack effect and pedestrian comfort.

Structural Design Concept

The building is located within one of the most active seismic zones in the world; a prudent selection of seismic resisting system is very crucial. Classified as Seismic Design Category D (ASCE 7-10), Signature Tower presents great challenges to engineers because of the high seismic reactions and extremely soft soil conditions.

Foundation

Drilled shaft bored piles with a mat foundation system was used for this project to support the weight of the building and resist overturning moments from wind and seismic loads. The tower mat is relatively thick (6.5 m to 7.5 m) to distribute vertical loads from columns and core to the bored piles. The drilled shaft pile foundation under the tower-mat is 1.2 m in diameter, with an effective length of 90 m to transfer the axial load of the tower to the hard silt and very dense sand. The bored piles develop their load carrying capacity through both skin friction along the perimeter and end bearing of the toe. Since the bored pile is relatively long, the working load will be mostly carried by its skin friction capacity. The piles, with 3.6 meter spacing, cover the 80-m-square mat to resist the axial load of the tower's weight. The total number of bored piles within the mat are also needed to resist the wind and seismic loads to acceptable limits of lateral deformations.

The shear strength and consolidation tests of the soil layer between 125 to 200 meters indicated that the layer is overly-consolidated. The strength and consolidation tests for the soil layer between 50 to 125 meters indicated that the layer is slightly over consolidated. The pile effective length of 90 meters is required to limit the total and differential settlement to acceptable limits due to compressibility of this soil layer. The consolidation settlement analyses were conducted

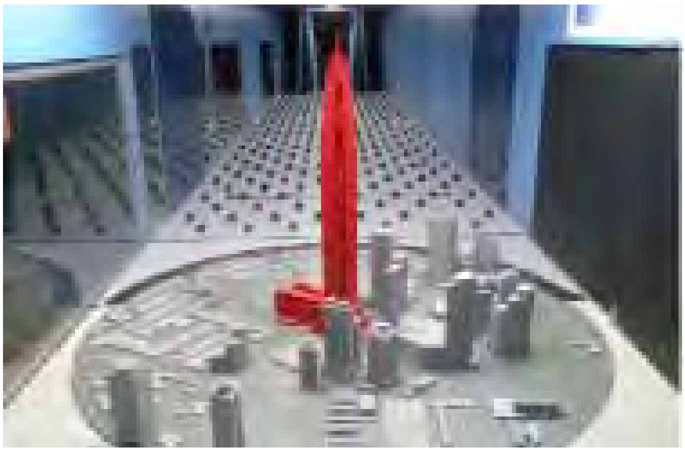


Figure 9. Wind tunnel study model (Source: RWDI, 2012)
图9. 风洞测试模型（出自：RWDI，2012）

和振荡周期率与塔楼自振周期较为接近。在地表下参考岩面SB对SLE和MCER生成地震输入。地震输入的生成是通过反应谱匹配技术，以确定由参数分解分析得到的目标反应谱。

从地表下参考岩面SB到地表面，地震输入考虑了在非线性时域波的传播。剪切波速分布来自于地震井下试验和周围噪音微脉动测量，以确定地表至深度约500米的地表下参考岩面的情况。从地表面到300米深，可以确定剪切波速达760米/秒的参考岩石面SB。图7表示了从地面到300米的深度的剪切波速分布。地震波的传播分析基于剪切波速的分布和地震动输入，并对0 - 10秒一系列不同的振荡周期进行放大。最终得到用于设计的基于SLE和MCER的反应谱，如图8所示。

风洞试验

对于超大建筑和超过50层以上高(200米高)的高层建筑，雅加达政府要求进行风洞实验。为了达到这个目的，该项目采用Rowan Williams Davies & Irwin Inc (RWDI)的2.4×2.0米边界层风洞设施（位于加拿大，安大略省，圭尔夫）进行了一系列的风洞试验。风洞试验采用比例尺1:500的模型，连同其周围直径600米以内的设施，进行高频动态天平(HFFB)实验。图9表示在实验室进行的风洞试验。把风力气候数值模型的风速值标定为：开阔地形梯度高度， 每小时平均风速为40m/s，发生频率为100年一遇。整体结构风荷载预测峰值概要如表1所示。根据风洞试验得出的基底剪力和倾覆弯矩分别约为地震荷载的46% - 60%和69% - 80%。因此，地震荷载主导了塔楼的抗侧力体系的设计。

预计在1%临界阻尼比下1年回归期的峰值加速度和10年回归期的加速度分别是6.0 milli-g和13 milli-g。这些数值分别低于国际标准组织(ISO) 1年回归期和RWDI标准下10年回归期对办公楼和住宅建筑的限值。因此，该预测加速度满足办公楼的舒适性要求。风洞测试也被用来研究幕墙风荷载，叠加效应和行人舒适性。

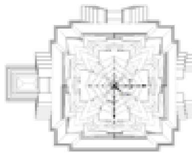
Moments (kN-m) 力矩			Base Shears (kN) 基础剪力		
My (Y轴力矩)	Mx (X轴力矩)	Mz (Z轴力矩)	Fx (X轴力矩)	Fy (Y轴力矩)	 Tower plan 塔楼平面
1.61 E+7	2.06 E+7	1.19 E+5	4.63 E+4	6.00 E+4	

Table 1. Summary of predicted peak overall structural wind loads at the ground floor (Source: RWDI, 2012)
表1. 地面层预计整体结构风荷载峰值总结

using computer programs UniSettle (UniSoft Ltd) and TCON (TAGA Ltd). The estimated net load acting on the foundation is 4,449,000 kN. The results of our analyses indicate that the tower's foundation would settle on the order of 170 – 180 mm (Langan International, 2012). About two thirds of the settlement would occur during construction.

Slurry Wall Construction of 1.0-1.2 m thick is used for the entire perimeter basement wall. The working condition for the slurry wall is separated in two stages: during the construction stage to retain the soil and top-down construction implications and at the service stage to resist the soil at-rest pressure, the groundwater pressure and dynamic seismic lateral earth pressure.

Upper Structure

Since Indonesia is located at the circum-Pacific seismic belt, a lateral load resisting system needed to be appropriately selected for the design. The tower utilizes a "Core-Outriggers-Mega Frame" system. It includes a hybrid concrete core, outrigger trusses, hybrid super columns and an exterior mega frame, which consists of super columns and belt trusses. The hybrid concrete core is linked to the eight super composite perimeter columns through two(2)-story high steel outrigger trusses at three locations along the building height. These structural components are intended to be the primary lateral load resisting system of the tower. The secondary system consists of a mega frame with its super columns and belt trusses, which are placed at six locations along the building height (see Figure 10).

The reason for selecting the above lateral load resisting system can be described as follows: The square concrete core with 31m wide faces efficiently encloses numerous elevators and stairs needed to service tower occupants, but it is not sufficient by itself to resist extreme overturning moments generated by lateral wind and seismic loads, as well as to control deflections and drifts to the required comfort level. The most economically feasible approach to resist overturning and improve stiffness is to engage outer columns to benefit from a longer moment arm. Hence, three sets of two-story outrigger trusses aligned with flange core walls are used to tie the core and exterior super columns together. The two-story outrigger trusses are located between levels 33~35, levels 58~60, and levels 91~93. A one-story head truss is located at levels 109~110 to control the drift at the tower's top. In addition, the tower is wrapped by a mega frame consisting of nine belt trusses linking the super columns together and transferring secondary column gravity loads to super columns. The one-story belt trusses are located between levels 10~11, levels 22~23, levels 47~48, levels 72~73, levels 83~84 and levels 109~110. Two-story belt trusses are located between levels 33~35, levels 58~60, and levels 91~93. The thickness of the core walls at the ground level is 1.1 m and decreases to 0.6 m at the upper floors in order to maximum the usable areas. The dimensions of the super columns are 3.5 m x 5.0 m at the ground level and decrease to 1.5 m x 1.5 m at the upper floors. These columns are straight at the lower floors and slope gradually at the upper floors to fit the tower's profile.

As part of the gravity system, the floor consists of composite floor decks with steel beams and girders. These composite floor decks with concrete solid slabs on top of metal deck are used to expedite the construction and decrease building self-weight. The tower's gravity load on every floor is supported by the core, super columns and much smaller gravity columns. The gravity forces in the gravity columns are collected by belt trusses and transferred to the super columns. This load path not only reduces the accumulated gravity forces taken by the gravity columns, but also helps to reduce tensile forces in the super columns due to lateral loads. At the top of each zone, gravity columns are connected to the bottom of belt trusses with vertically slotted

结构设计概念

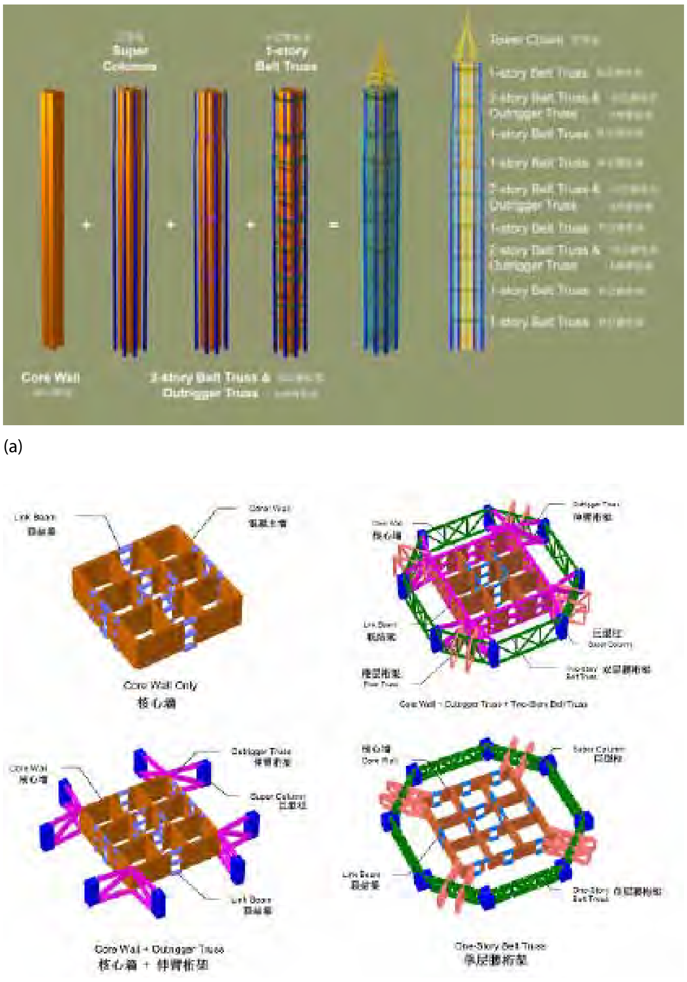
该建筑物位于世界上最活跃的地震带之一，谨慎地选择适当的抗震体系就显得非常重要。由于强地震反应和极软弱土壤地基条件，使Signature塔楼抗震设计等级为D级(ASCE 7 - 10)。这给工程师提出一个极大的挑战。

基础

在这个工程中采用钻孔灌注桩与筏式基础体系，以支承建筑物的重量和抵抗由于风荷载和地震力产生的倾覆力矩。塔楼筏式基础较厚(6.5米到7.5米)，用于承受从柱子和核心钻孔灌注桩传来的竖向荷载。塔楼筏式基础下桩基直径为1.2米，有效长度90 m，以便把塔楼的轴向载荷传到硬淤泥和高密度的沙土层。钻孔灌注桩通过沿周桩表面摩擦及桩端获得承载力。灌注桩较长，因此桩上的荷载主要由桩表面摩擦力承担。间距为3.6米的群桩分布于80m见方的筏板下，支承塔楼竖向力。筏式基础下所布钻孔灌注桩的数量还需满足由风荷载和地震荷载引起的建筑变形的要求。

125至200米之间土层的抗剪强度和固结试验表明，该土层是超固结土。对于50 至125米土层的应力和固结试验表明，该土层为轻度超固结土。由于土层的压缩性，90米桩有效长度可把桩的总沉降量控制在可接受的限度。使用UniSettle(UniSoft公司)和TCON(TAGA公司)软件进行固结沉降分析，得出作用于基础的净荷载是4,449,000 kN。分析结果表明，塔楼基础将会沉降约170 - 180毫米(Langan International, 2012)。约三分之二的沉降会发生在施工期间。

整个地下室外墙使用1.0 - 1.2米厚的地下连续墙。地下连续墙的工作分为两个阶段：在施工期用于挡土和实施逆作法施工，在使用阶段用于抵抗土静压力、地下水压力和地震产生的侧向土压力。



(a)

Figure 10. (a) Tower isometric view and (b) Detail of each lateral resisting system
图10. (a)塔楼等距视图，(b)抗侧力体系细节

connections to release potential stresses due to creep, shrinkage and differential movements.

Since a core wall outrigger system is not listed in the lateral system in ASCE 7-10, the designer was required to use Performance-based Design as an alternative analysis method. The Performance-based Design incorporates a series of time history analyses with seven sets of acceleration records in order to evaluate the building's performance under different levels of seismic hazard, in addition to the conventional code-based design. By carrying out this design method it is hoped that an efficient and safe structure can be achieved.

The Podium structure located beside the Signature Tower was designed to resist the lateral forces by mainly employing concrete moment frames. Special moment resisting frame (SMRF) was selected as a lateral resisting system above the ground floor and moment frame with shear wall was designed to take lateral loads at basement floors. Thus all moment frames on this structure have been designed to satisfy special moment frame requirement stated in ACI-318. The high-rise tower structure and the podium structure have different structural behaviors, so expansion joints are an effective way to separate the structures to avoid the structural interference between dissimilar structures. Expansion joints were placed between the tower and the above-ground podium.

The podium's gravity framing system is mainly a one way concrete slab system with concrete girders and filler beams on typical bays. Concrete slab thickness varies from 125 mm to 180 mm, depending upon the floor's usage. A steel truss system was selected for supporting the roof structure, which is accessible and public space with a garden. Steel trusses on the roof makes a spacious area of 56 m x 88 m, without any columns at the floor. The steel trusses are combined with steel sections embedded in concrete columns and some horizontal bracing on the roof level. These help diaphragm the forces spreading out to other frames.

Closing Remarks

The 111-story Signature Tower will be reaching high in the sky of Indonesia prior to 2020. The designers dealt with a series of design challenges, including the soft soil conditions and high seismicity, by using extensive site-specific earthquake hazard investigations, a rigorous soil testing program and state-of-the-art analysis methods. These are highlighted by:

- New Concept Of Risk-Targeted MCE from Site-Specific Earthquake Hazard Analysis has been adopted for seismic design criteria for this tower.
- The Performance-Based Design incorporates a series of time history nonlinear analyses with seven sets of acceleration records in order to evaluate the building's performance under different levels of seismic hazard.
- The 90 m effective deep bored pile foundation, below the lowest tower-mat, is designed to sufficiently penetrate into a very stiff to hard overly-consolidated clay layer for stability and to limit the settlement of the building.
- "Core-Outriggers-Mega Frame" system is the most appropriate lateral load resisting structural system and gravity load resisting elements for the tower in this seismicly prone area. Structural analyses show that the tower meets all design criteria as required by the current design guidelines and standard of practice.

上部结构

由于印度尼西亚位于环太平洋地震带，就需要在设计中选择一个合适的结构体系来抵抗侧向荷载。塔楼采用“核心筒-外伸臂桁架-巨型框架”系统。它包括由内埋钢板的混凝土核心筒，外伸臂桁架，以及由巨型柱与腰桁架形成的巨型外框架组成。核心筒通过沿塔楼高度方向布置的三道外伸臂钢桁架与八根巨型组合柱相连。这些构件将作为塔楼主要的抗侧力体系。塔楼的第二道抗侧力体系是由巨型柱和沿塔楼高度方向布置的六道腰桁架组成(见图10)。

选择上述抗侧力体系的原因如下：边长31米的方形混凝土核心，内部布置为塔楼使用者提供的电梯和楼梯，但它本身不足以抵御由侧向风和地震力所产生的极大的倾覆力矩，也不能使挠度和层间位移角满足舒适度要求。提高抗倾覆并增加刚度的最经济可行的方法是加长外层立柱的弯矩力臂。因此，设置三套两层高的外伸臂桁架，将核心筒和外围巨柱连在一起，使其与核心筒一起工作。两层高的外伸臂桁架分别位于33~35层、58~60层、91~93层之间。上面位于109~110层的是一层高的帽桁架，用于控制塔楼顶部位移。此外，塔楼被一个巨型框架包裹着，该框架由9个环带桁架和与之相连的巨型柱组成，使重力柱的荷载通过环带桁架传向巨柱。一层高的环带桁架分别位于10~11层、22~23层、47~48层、72~73层、83~84层和109~110层之间。而两层高的环带桁架分别位于33~35层、58~60层、91~93层之间。在地面标高处的核心筒墙厚度是1.1米，到上部楼层后墙厚减少到0.6米，以便最大限度增加使用面积。在地面标高处的巨型柱尺寸是3.5米x 5.0米，到上部楼层后减少到1.5米 x 1.5米。这些柱在较低楼层处是竖直的，到上部楼层就逐渐倾斜，以适应塔的外形。

作为重力体系的一部分，楼板由混凝土组合楼板和钢梁组成。用这种由压型钢板和其上的混凝土板构成的组合楼板，可以加快施工进程时间并减少建筑自重。塔楼每层的重力荷载由核心筒、巨柱和较小尺寸的重力柱支承。重力柱上的重力荷载由环带桁架转换并传递到巨柱上。该荷载路径不仅降低了由重力柱的内的累计荷载，而且也能减小巨型柱由于侧向荷载引起的拉力。在每个区域的顶部，重力柱通过垂直方向的开槽节点连接到环带桁架底部，以释放由于蠕变、收缩和微小位移引起的潜在应力。

由于核心筒外伸臂桁架体系在ASCE 7-10的侧向抗力系统中没有明确列出，因此需要设计师采用性能化设计进行辅助性分析。除了传统的基于规范的设计，设计人员采用7套地震记录的时程分析法进行性能化设计，以评估不同级别地震灾害下的塔楼结构的性能。通过实施这一设计方法，能够得到一个较为高效和安全的结构。

紧邻Signature塔楼的裙房结构主要通过混凝土框架体系来抵御侧向力。设计人员选用特殊刚结框架（SMRF）作为地面以上的抗侧力体系，框架-剪力墙体系作为地下室的抗侧力体系。因此，所有刚结框架的设计都能满足ACI-318中有关特殊刚结框架的要求。塔楼结构和裙房结构具有不同的结构性能，因此，设置伸缩缝是一种行之有效的方法用来消除不同结构之间的干扰。伸缩缝布置在塔楼和地面以上裙房之间。

裙房的重力体系主要由混凝土梁和混凝土单向板系统组成。混凝土板厚度为125 毫米至180毫米，厚度取决于楼板的用途。选用钢桁架支承带有花园的公共空间的屋顶。屋顶钢桁架可以形成面积为56米x 88米的无柱大空间。钢桁架与埋置于混凝土柱中的型钢相连，并在顶层布置水平斜撑，有助于将隔板力传递至框架中。

结论

111层的标志大厦将于2020年前在印尼建成。设计师要应对一系列设计上的挑战，包括软土地基条件和高频率的地震活动，通过对目标地块的地震灾害研究、严格的土力学试验和运用最先进的

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结构分析方法来确保方案的可行性，重点包括：

- 在这座塔楼抗震设计准测中采用了针对目标地块地震灾害性分析的新概念，风险控制MCE。
- 性能化设计采用7套加速记录一系列的时程分析，以评估在不同水平的地震灾害下的建筑物性能。
- 在塔楼筏式基础下设90米有效深度的钻孔桩基，使桩基能穿过坚硬土层达到饱和固结粘土层，以稳定和限制建筑物的沉降。
- 在这个地震频发地带，“核心筒-外伸臂-巨型框架”是最合适的抗侧力体系和重力体系。结构分析表明,该塔楼的设计能满足现有全部设计规范和实施标准。

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