Title: **Raffles City Chongqing: A Skyscraper City within a Development**

Authors: Andrew Luong, Director, Arup
Michael Kwok, Director, Arup
Patrick McCafferty, Associate Principal, Arup
Penny Cheung, Associate Director, Arup

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Raffles City Chongqing: A Skyscraper City within a Development

Andrew Luong
Director

Arup,
Shanghai, China

Andrew has 20 years of experience in structural engineering. He joined Arup in 1995 and has developed his career working in Australia, Hong Kong, London, India, and China. Andrew has delivered a portfolio of successful and award winning projects, involved from inception through completion. His notable projects include Pazhou Mixed Development, (Guangzhou), CCTV Headquarters Building (Beijing), 2 International Finance Centre (Hong Kong), Rajiv Gandhi Airport (Hyderabad), Run Run Shaw Creative Media Centre (City University of Hong Kong), and Olympic Green Convention Centre (Beijing).

Michael Kwok
Director

Arup,
Shanghai, China

Michael graduated at Imperial College in Civil Engineering and has more than 29 years of experience in structural engineering design and consulting. He joined Arup in 1986, and he has spent most of his career in Hong Kong, mainland China with intervals in the UK. He has been in-charge of many high profile building and infrastructure projects in mainland China from inception to completion. These include the National Stadium (Bird's Nest), CCTV Headquarters Building, China World Tower and Beijing Capital International Airport Terminal 3; Korean Pavilion and Danish Pavilion for Shanghai World Expo; Shenzhen Stock Exchange Square and Guangzhou International

Patrick McCafferty
Associate Principal

Arup,
Boston, USA

Patrick McCafferty is an Associate Principal with Arup. He began his career as an American Scholar in Arup's London and New York offices upon receiving degrees in structural engineering from Cornell University. He currently leads the structural engineering practice for Arup in Boston. Patrick specializes in the design of innovative and architecturally expressed structures. His experience includes international management and the engineering design of museums, performance venues, airports, mixed-use development, and sculpture. Patrick is a frequent architectural juror at universities throughout the United States and abroad and is a member of faculty at Harvard University.

Penny Cheung
Associate Director

Arup,
Chongqing, China

Penny graduated with the bachelor degree in civil engineering at the University of Hong Kong with Master degree in Civil Engineering and in Real Estate. Penny is Arup Chongqing office leader and the Project Manager for the Raffles City Chongqing project. He is professional structural engineer and has been working in Arup Hong Kong, Shanghai office and more recently Chongqing office managing a team of over 40 staffs. He has extensive experience in leading and managing multi-disciplinary engineering team for large comprehensive development in Mainland China and Hong Kong. In his fourteen years career, He has been involving in projects

Abstract

Raffles City Chongqing is a comprehensive mixed-use development with an overall gross floor area of approximately 1,100,000 square metres. The development encompasses a transportation hub, luxury residential, high end serviced apartments, offices, hotel, retail, and substantive public space programs. The key tall building features are six 250m high and two 350m high towers, all curved. A 300m long, glazed "sky bridge" sits atop four of the 250 tall towers, and connects to the two 350m tall towers. The physical linkage in the air of these six towers creates a mini-"skycraper city" in itself. This is a truly unique architectural topography, the design and delivery of which required new thinking and solutions to the structural engineering, as well as all building design disciplines.

Keywords: "Hybrid" Outriggers; Inter-Connecting Towers; Performance-Based Design; Skyscraper City

The super-scale development of Raffles City in Chongqing will become a new landmark for the city. Located at the heart of Chongqing, at the junction between the Yangtze and Jialing rivers, the site is charged with historic and symbolic significance. The super-scale development design by internationally acclaimed architect Moshe Safdie is inspired by images of great Chinese sailing vessels on the river. It pays tribute to Chongqing's noble past as a trading centre and also serves as a symbol of the city thriving present and promising future. Figure 1 shows architectural images of the development.

Arup is appointed to provide structural, civil, fire safety, building sustainability services for all design stages through the construction site services. This paper presents the structural engineering of this grand scale project, sharing on various break-through, innovations, and major structural achievements.

Towers

In any development, the tall tower always stands out and become a focal point of the design in different ways. In the Raffles City Chongqing project, the tall towers draw additional discussion points due to their large number, slenderness, curvature, and most headline-

Figure 1. Architectural images of the development (Source: Arup, courtesy of Moshie Safdie Architects)

grabbing, location of the conservatory structure on top of four towers and linking six of them.

There are a total of eight towers in the development. The two towers in the north are 350m in height. Six towers of 250m height line up to form the south towers. Figure 2 is a 3D Revit model of the development showing the towers.

North Towers

The two north towers serve a program mix of office, hotel and apartment. These towers are very slender, with footprint dimensions of 38m by 38m, and slenderness ratio of about 9.4. It is worth noting that the Chinese Code recommends tower slenderness to be around 7.0. Extensive schematic studies were carried out early in the design to identify the most appropriate structural system for the towers. The final chosen structural system caters to the architecture of the mixed program, and is very cost sensitive.

Material-wise, the towers are of typical high-rise typology, with a reinforced concrete core and composite construction in the vertical and floor framing systems.

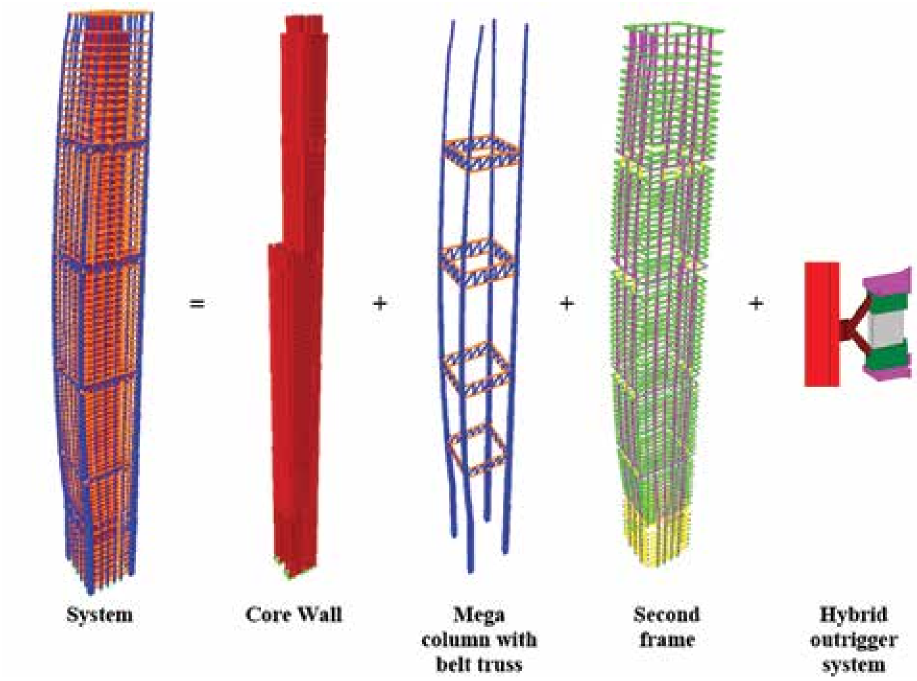


Figure 3. North towers structural stability system (Source: Arup)

The stability structural system comprises:

- Reinforced concrete core
- 4 corner mega-columns
- Belts trusses
- Hybrid outriggers (refer to separate section in this report describing in detail this innovative system)
- Perimeter moment frame which has a secondary contribution to the main mega-column/belt-truss frame.

Refer to Figure 3 below showing the tower stability system.

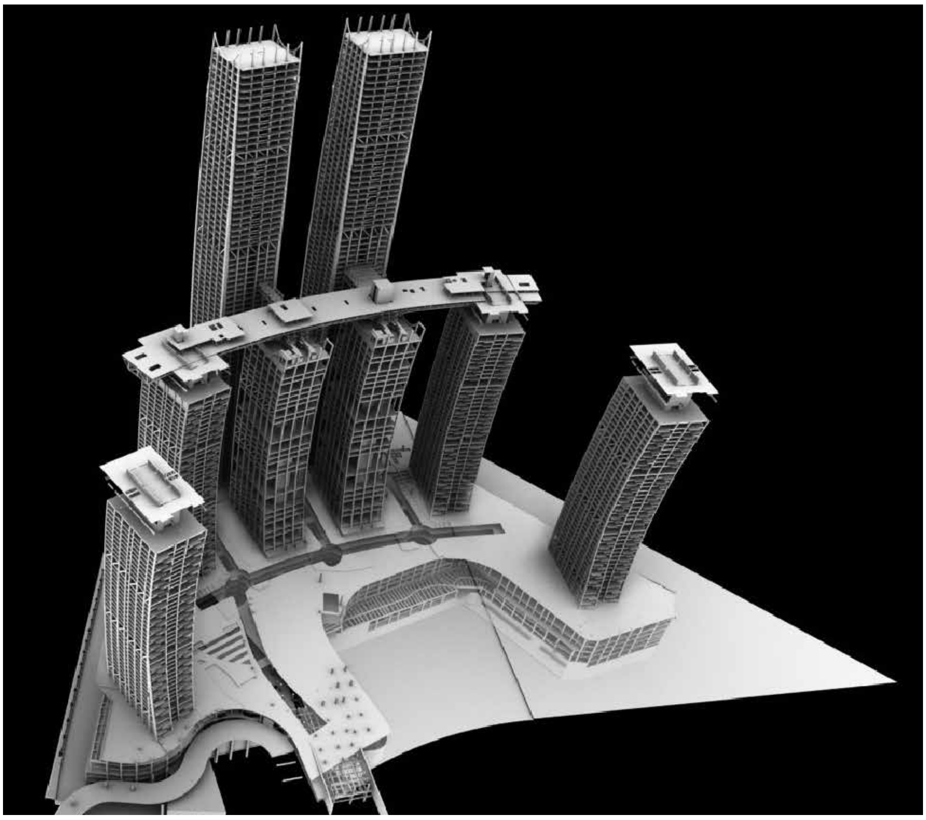


Figure 2. 3D Revit model of development (Source: Arup)

South Towers

There are six 250m tall towers in the project collectively described as the south towers.

The towers are similar in architectural form and shape, with different functions. Similar to the north towers, the south towers are very slender (in the east-west direction). They are also curved in elevation.

The most western (T1) and the most eastern (T6) towers are standalone mirrored forms. The central four south towers T2, T3S, T4S, and T5 are connected by supporting the conservatory structure on top.

South towers structural systems

The 6 south towers carry different programs, with T1, T2, T5, T6 being luxury residential, T3S office, and T4S a mix of office and luxury residential.

The towers structural material is mainly reinforced concrete, with some of the columns (low zone) in composite construction, and the belt truss and outriggers (in T2, T3S, T4S and T5) a mix of composite and structural steel. The floor systems for the south towers are of reinforced concrete beam-slab framing.

The structural stability system of the towers are characterized by:

- Reinforced concrete core
- Perimeter moment frame with some columns in composite sections.
- Belts trusses
- Limited number of outriggers trusses in the towers supporting the conservatory. The belt and limited outrigger trusses are mainly to provide for the horizontal stability system for wind and seismic action.

The conservatory structure

Undoubtedly the most noticeable structure in the Chongqing Raffles City development will be the Conservatory structure. This is also the most complex structure in the development, and a world first. It is a 300m long continuous structure which sits astride four towers at a height of 250m above ground.
The structure is indeed a world first – highrises are common, as are long span structures – but the combinations of long span structures on top of highrises has no precedence. Perhaps the closest resemblance to the conservatory can be drawn from the Marina Bay Sands development in Singapore. Yet that is on a much smaller scale, and Singapore does not experience the design

Figure 5. LS-Dyna model for non-linear time-history analyses in conservatory articulation (Source: Arup)

wind conditions in Chongqing, nor is it seismic. (Figure 4 is a reference comparison of long span and cantilevered horizontal structures at height.)

At the outset, the structural challenge has been to determine the articulation of the conservatory in relation to its supporting towers, i.e. whether and how to fix or float the conservatory on top of the four supporting towers.

Design options where the conservatory is fixed to or isolated from the towers, in various permutations, were compared and their impact on building cost considered. The software LS-DYNA was used to perform the intensive non-linear time-history seismic analytic modeling studies. Figure 5 shows the LS-Dyna model for non-linear time-history analyses of the conservatory articulation studies.

These studies supported the hypothesis that the isolation options are beneficial in terms of reduction of shear forces measured at the base of the towers. In the best case, the base shear reduction can reach 30% compared to the fixed conservatory option.

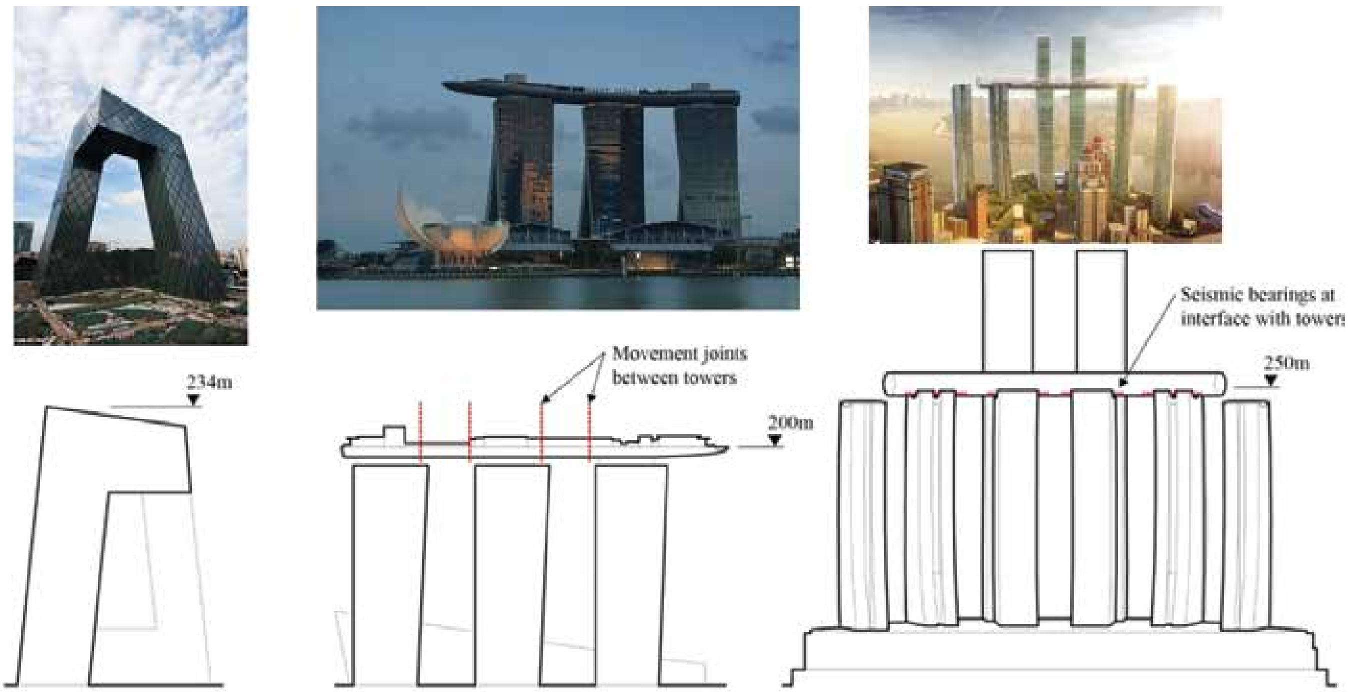


Figure 4. Comparison of long span and cantilevered horizontal structures at height (Source: Arup)

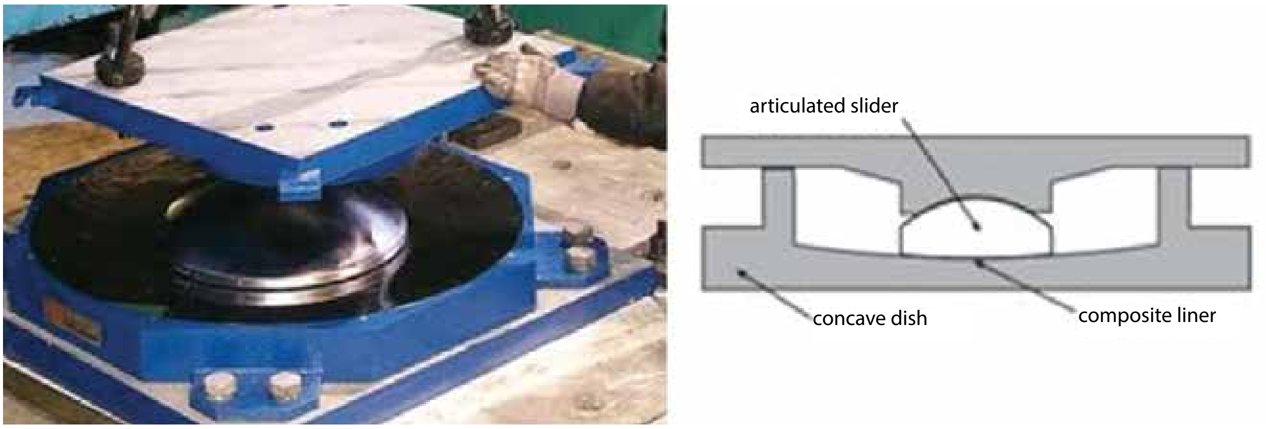


Figure 6. Friction pendulum bearing (Source: Arup, courtesy of Maurer Soehne GmbH & Co)

The chosen articulation solution is one of isolation using a combination of friction pendulum bearings (FPBs), lead rubber bearings (LRBs), and dampers. The final solution utilizes a total of 26 FPBs and 16 dampers. Figure 6 shows a typical friction pendulum bearing device. For the project, the friction pendulum bearings are in the magnitude of 2m diameters.

The chosen articulation philosophy is that the conservatory is performed as if fixed during serviceability including wind and service limit earthquake (SLE, or the common design earthquake), and the conservatory to dynamically move under design based earthquake (DBE, or moderate earthquake in Chinese Code) and maximum considered earthquake (MCE, or rare earthquake in the Chinese Code) to dissipate the seismic energy.

As to the conservatory structure itself, it is made of structural steel, composed of three primary trusses, interconnected by secondary steel trusses. The conservatory is enclosed by a light-weight space truss enclosure (see figure 7).

Hybrid outrigger

As mentioned earlier, the slenderness and height of the north towers are a major challenge to the structural design. The towers are designed for wind and seismic action. Chongqing being in a moderate seismic intensity zone, seismic action for the intermediate and rare earthquakes is critical to the towers design. The design of the towers, and conservatory connection, are affected by both wind and seismic action, depending on the level of the earthquake.

The adopted structural stability system addresses these problems through the use of outriggers. In the design process, Arup modified the outriggers and developed the hybrid outrigger system (patent applied and approved).

Under normal operation, including design wind load, and the common Level 1 earthquake loading (this is the frequent earthquake with an expected return period of 100 years), the system behaves in the same way as a normal outrigger system. However, the building also requires resisting the medium and rare earthquakes. Adopting a standard outrigger to the building to resist the higher modes of earthquake would be very expensive. Thus the hybrid outrigger was developed.

The hybrid outrigger system comprises three components - an energy dissipation fuse, steel bracing, and reinforced concrete wall

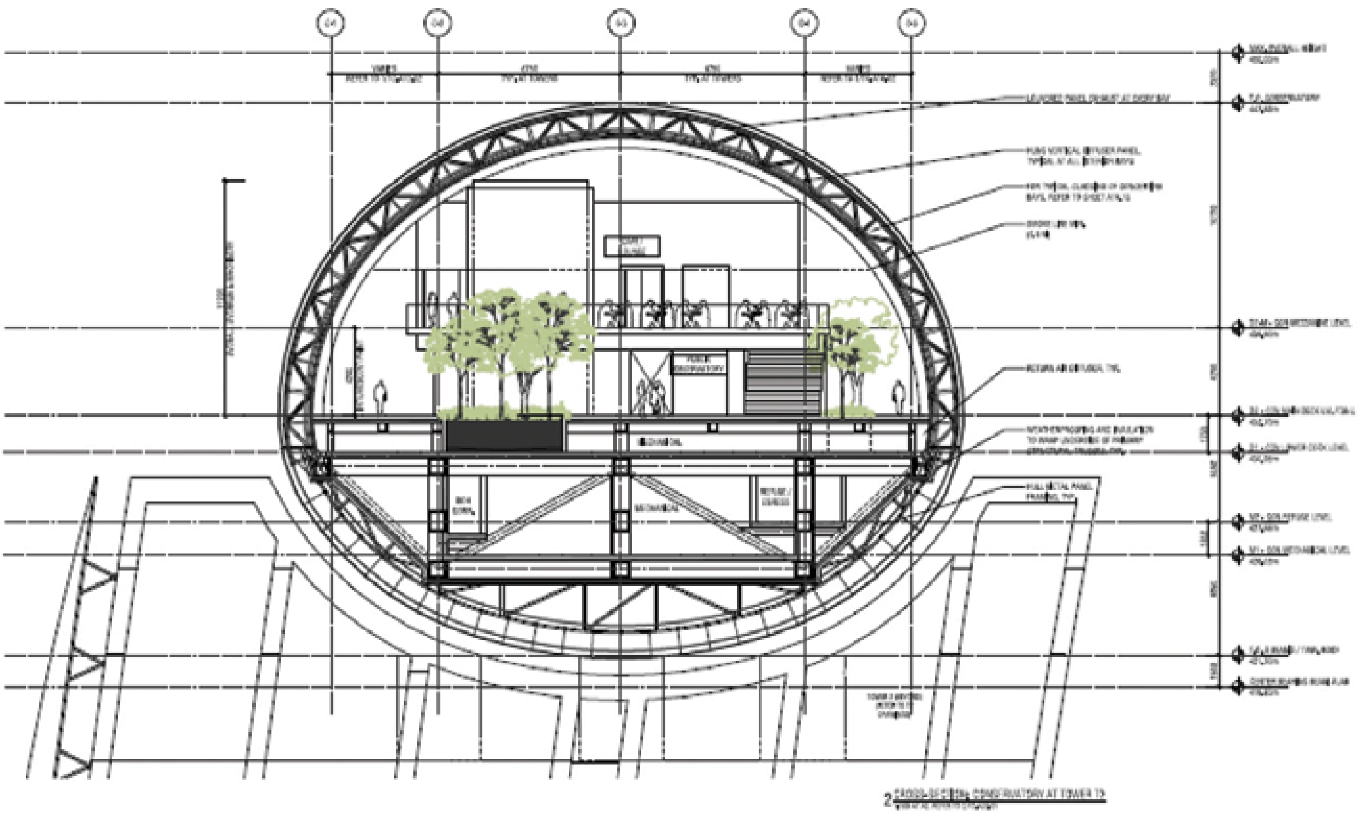


Figure 7. Section showing light-weight trussed enclosure to conservatory (Source: Arup, courtesy of Moshie Safdie Architects)

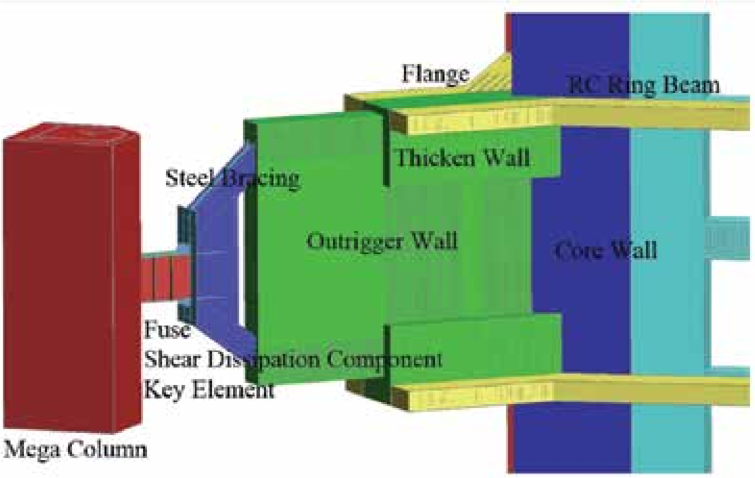


Figure 8. Hybrid outrigger system (Source: Arup)

Figure 9. Prototype testing of the hybrid outrigger system (Source: Arup)

outrigger. Hybrid outrigger system (Figure 8) innovative design is able to have 7% improvement on the tower lateral stiffness at elastic stage compared to traditional design. The system operates whereby, at the higher loading conditions, the fuse element is designed to yield first. This protects the reinforced concrete wall and the rest of the system from damage. The fuse can be readily replaced after yielding. Compared to the standard outrigger system (which is predominantly structural steel), the hybrid outrigger system constitutes a cost saving of approximately 40 million RMB.

Since the hybrid outrigger system relies on a yielding sequence, different steel grades are designed for each part. The fuse is designed to yield the first, so Q225LY steel is used. The steel bracing connecting the fuse and outrigger wall is designed to be made of Q235B steel. The reinforced concrete wall is thickened near the core wall corner to ensure a strong connection.

As the hybrid outrigger system is a newly developed system, tests have to be carried out to verify its adequacy, and as part of the design approvals process. Three tests have been specified and completed to high satisfaction. The first experiment involved testing the shear capacity and lag properties of the fuse. The geometry of the fuse was optimized after the experiment. The second experiment tested the load path through the three components, leading to the optimization of rebar placement in the reinforced concrete wall. The third and last experiment verified the performance of the whole system, including behavior, capacity, deformation, and element characteristics. Figure 9 shows prototype testing of the hybrid outrigger system.

Wind engineering

Wind engineering is a must for a development as this, where there is a mini-city of interlinked high rise buildings. The site will experience different wind conditions as it is located at the intersection of Jialing River and Yangtze River.

The design team specification for the wind tunnel studies required determination of:

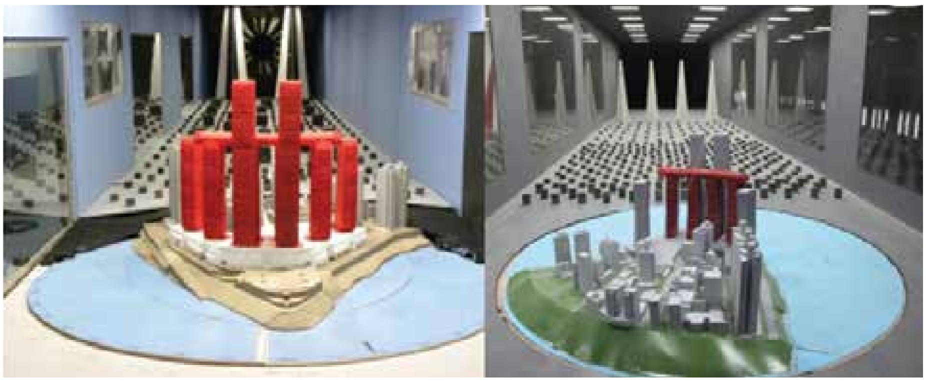
- Wind field parameters because of the complicated topography which includes rivers and mountains;
- Design wind loads, especially the across-wind load of the two 350m north towers and torsional wind load of multi-tower because of the complicated building shapes;
- Interference effect of the many surrounding buildings.

The following wind engineering studies were carried out:

1. Wind climate analysis to determine the right design wind speed and wind speed-direction reduction factors
2. A 1:3000 scale topography effect test to determine the wind field parameters, such as mean wind speed profile, turbulence profile and turbulence integral scale at typical heights;
3. Multi-high frequency force balance (MHFFB) wind tunnel test to determine the design wind loads of multi-tower structure at the same time;

a.

b.



c.

Figure 10. Wind tunnel test photos: a. 1:3000 topography test, b. 1:400 MHFFB Test, c. 1:400 HFPI Test from two different independent wind tunnel labs. (Source: Arup)

4. High frequency pressure integration (HFPI) wind tunnel test in two independent different wind tunnel lab to determine the structural wind loads of the multi-tower structures, and HFPI wind tunnel test of the four single towers;
5. LS-DYNA time-history analysis to check the performance of the isolators between the conservatory and top of 4 towers under the wind load in different return periods.

Through the wind engineering and wind tunnel testing works, the design wind loads were derived to apply for different design needs. Typically the adopted structural wind loads were smaller compared to the Code, providing an economic saving. Figure 10 shows some wind tunnel test photos. Both the HFFB and HFPI tests models are 1:500 scale.

Basement and podium design strategy

This development is the largest single investment by any Singapore company in China, with development cost expected to reach RMB21.1billion. The podium retail component, at around 250,000 square meters, is also possibly the largest in China, covering a plan dimension of approximately 400m by 250m.

Complementing the retail program, office, residential and hotel amenities, the podium also serves as a very important transportation hub which includes new integrated bus terminal, metro station and ferry terminal. Figure 11 shows a Revit extract of the podium and some major program zones.

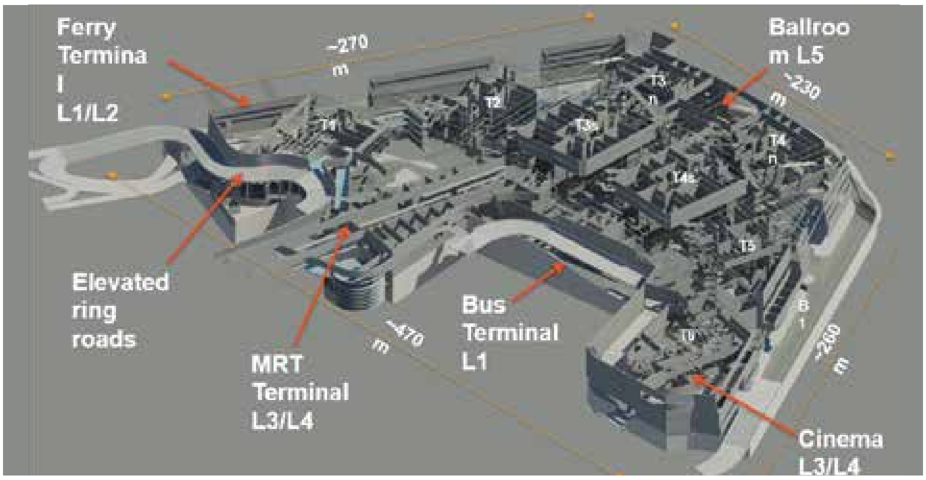


Figure 11. Revit model extract of the podium and major program zones (Source: Arup)

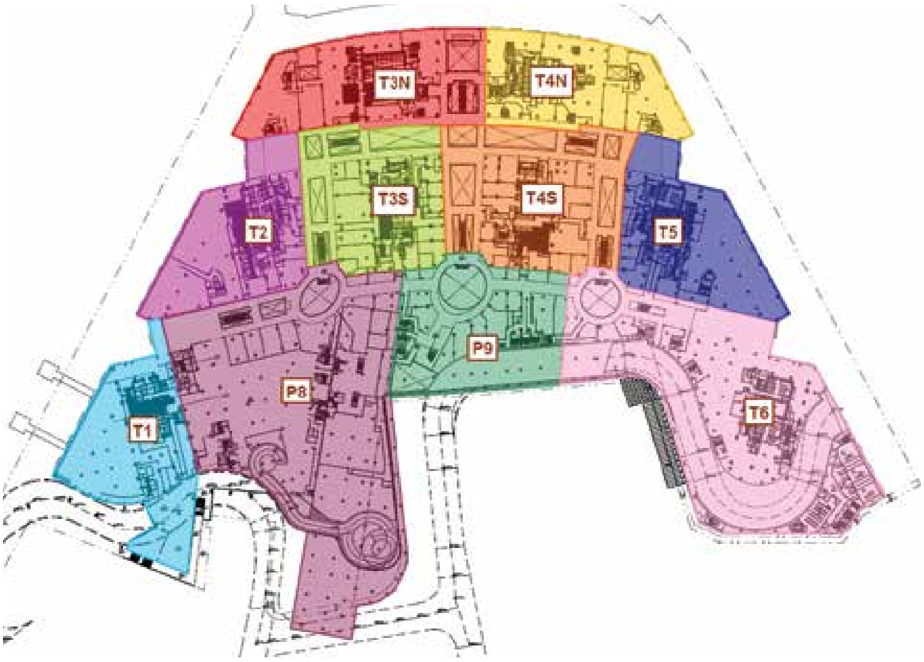


Figure 12. Movement joints in the podium structure (Source: Arup)

The basement and podium mass of the development consists of 9 stories total. Three levels are basement housing MEP, car parking and back of house usage.

An important characteristic to note is that the basement is not underground on all sides. Due to the nature of the site, with the bedrock and ground sloping towards the east, west and north of the site, only the south side basement wall is underground. The basement is exposed for much of the other three sides.

The design strategy from the very beginning was to design a fully connected basement at every level with no permanent joints - S6, B1, B2 and B3 integral with the basement retaining wall – what is essentially a big concrete box! The benefits of having no permanent joints are obvious to functional needs, architecture, and operation and maintenance. However this approach introduces challenges to the structure and construction. There is a separate section in the paper addressing the long structure without joints.

The basement box was designed as stiff enough to resist all the horizontal shear forces (from wind, seismic, and retained soil pressure from the south of the development) from the towers and the podium itself as the basement on east, west and north sides are semi open. The basement is essentially a downward continuation of the podium structure, with added shear walls and moment frames as necessary. Thus the shear walls and moment frames provided the load path to the base.

Above the S6 level, a number of movement joints are introduced into the podium. The location of the movement joints have been carefully considered addressing different needs, and aligning with the tower masses and podium skylight locations. Refer to figure 12 showing the podium massing breakup by movement joints.

The movement joints are placed with each individual tower integrated with a section of podium (like a surrounding podium island). The tower stability system assists in stabilizing the section of podium. Slabs will cantilever to the void edges, thus creating column free or single column movement joints.

Roof garden

One of the most unique aspects of the podium is the sky garden on the podium roof. The roof is continuously sloping with a 5% gradient from the north to the south. The roof was designed as a big park with many sky-lights for lending more light into the podium levels. There are swimming pools for entertainment, water features and large deep planted areas to imitate the natural environment and also heavy fire access loading. From the structural point of view, the structural elements shall be designed to work efficiently to achieve the minimal structural zone (the structural depth was confined in

Figure 13. Site location (Source: Arup)

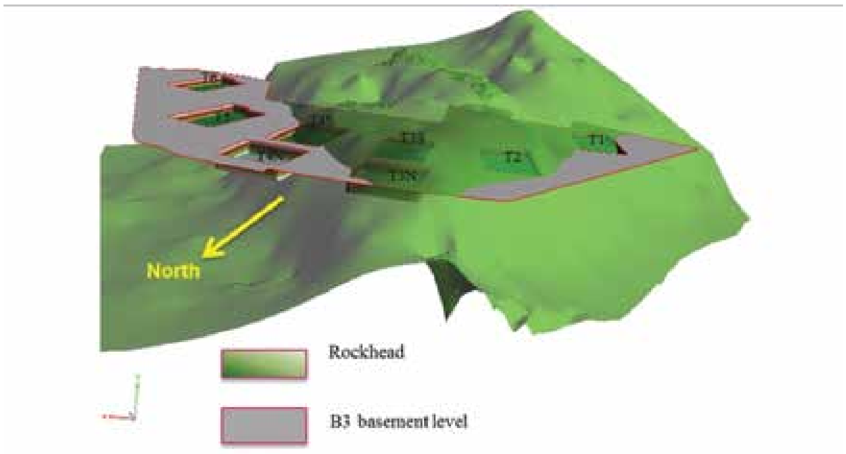


Figure 14. Rockhead contour (Source: Arup)

many areas to meet the finished architectural level and headroom requirements) under the heavy loadings, whilst respecting the complicated movement joint details to build up the beautiful "forest". The challenges to the roof garden structure include heavy loadings from fire trucks, deep planting, long spans, headroom pressures, and other issues.

Structure and MEP integration

One of the most challenging aspects of the podium design has surely been the vast coordination efforts required between structure and MEP servicing. The entire podium make-up has been fully modeled in Revit by the architect and the structural engineer in order to facilitate the clash detection and reduce issues on site.

Design of the basement box

The typical measurements for the basement floor in the project are 270m long, 400m width and 90,000m2 in area. As referred to in the basement introduction, the basement structures are designed as a whole without structural joint.

In the design of very long structure, the common approach is to add more reinforcement into the structural slab and foundation raft to withstand the shrinkage and thermal stress. Last cast strips are introduced to reduce the shrinkage effect. However this approach often leads to an excessive amount of additional reinforcement.

Restraint from foundation.

In standard practice, rigid pins were commonly used to simulate the support foundation regardless the foundation type. For this development, considering the scale of pile foundation, solid elements rather than springs were used in simulating hand-dug caisson piles in pile reaction analyses by Plaxis FEM, this is able to consider the flexural rigidity of the piles; in addition, horizontal spring is introduced to simulate soils and rocks around the piles, as compared with the rigid pin, the relative stiffness of pile is small. The smaller stiffness of pile give a certain amount of freedom for the base slab to expand and contract while help to release stress in the base slab and the rest of the basement floor.

Appropriate time and ambient temperature for concreting the last cast strip.

It is a known fact that, the longer the time after final set of concrete and the lowered temperature when late cast strip is concreted, the lower the ensuing shrinkage and thermal stress. However, delaying the late cast strip construction is always a challenge to construction scheduling and site progress. Choosing to cast the strip in lower temperature also means restricting the construction to fewer suitable days in the year. In this project, sensitivity analyses were carried for the time (with consideration of construction sequence) and ambient temperature. Based on the results, an appropriate ambient temperature and time after final set of concrete were selected.

As compared with traditional analysis approach without putting construction sequence and support stiffness in consideration, a comprehensive analysis could obtain a more realistic shrinkage and thermal stress. Eventually it made the construction of this very long structure possible and practicable for the Raffles City Chongqing project.

Site slope stability

The project site is located at the confluence of the Jiangling River and the Yangtze River. The site is basically sloping gently from south to north, whilst sloping down significantly to west and east sides. See figure 13 for the site location.

It is envisaged that, at west slope, there exist potential sliding interfaces or fissures among bedrock, which are dipping down from east to west; whilst the east slope is basically fill slope. Both side slopes impose potential stability problems to the project site.

The ground geology is basically composed of miscellaneous fill containing certain construction wastes, salty clay, cobble soil and cobble, underlain by interspersed mudstone, sandstone or sandy mudstone with different degree of decomposition. The rockhead level (moderately and slightly decomposed rock) is higher in the south and middle areas, lower in the north, west and east areas, which is similar to the site topography. See figure 14 for the rockhead contour.

In order to maintain overall site stability under static and seismic conditions, stabilizing piles were introduced to prevent potential sliding and to reduce lateral deformations. Various loading combinations under static and seismic scenarios were considered in the site stability analyses. Relevant geological and hydrological conditions were assessed carefully and taken into consideration. Residual Thrust Method, slope stability check by OASYS Slope and Plaxis 2D finite method were adopted to check the slope stability and ground movements. During design stage, stabilizing piles with various diameters, construction length and spacing were proposed around the crests of slopes. It was found from the Plaxis 2D FEM analysis that the ground movements were excessive if without stabilizing piles. In terms of slope stability check, if without stabilizing piles, the FOS of slope stability are basically less than the code requirements (i.e., 1.35 for static cases; 1.15 for seismic cases); but with the designed

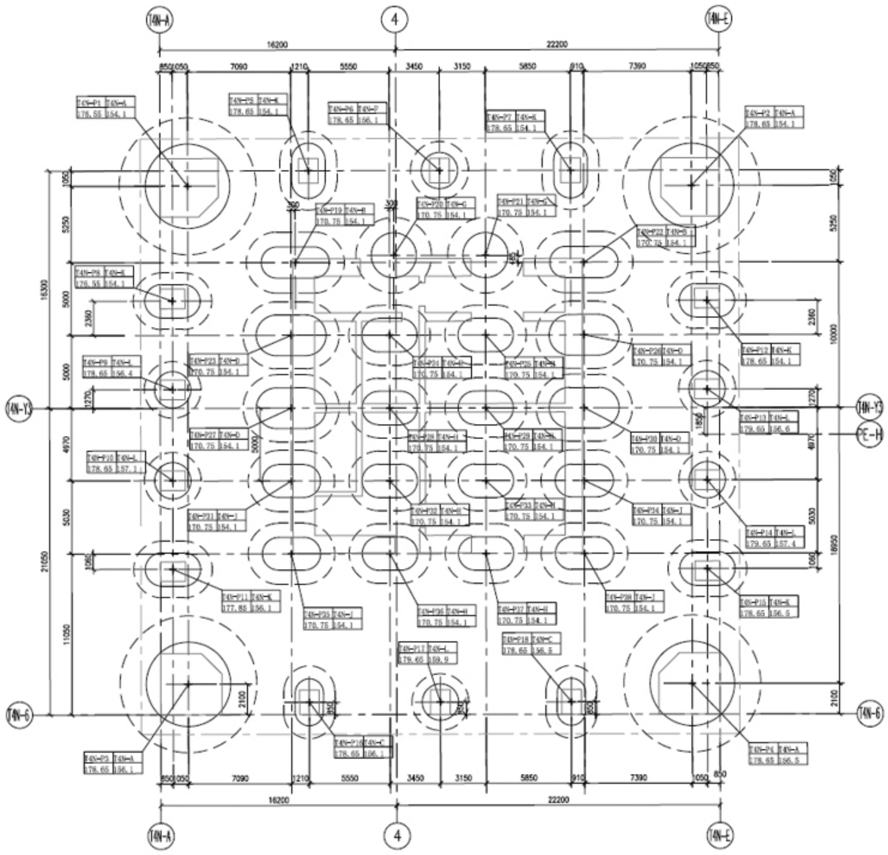


Figure 15. Foundation plan of the north tower (Source: Arup)

stabilizing piles, along with necessary structural measures, respective FOS of both east and west slopes under both static and seismic conditions can be secured.

Foundations

As discussed in the previous section, the ground has varied mix of shallower rockhead level around the south and middle areas, whilst deeper at other areas. In addition, thick miscellaneous fill, cobble soil and cobble strata are noted in the east area of the site.

At scheme design stage, in view of the loading schedules of tower superstructures and the complex site conditions, machinery bored pile and hand-dug caisson options were studied in terms of constructability, construction speed, cost, site constraints, local practice and regulatory requirements. Relevant pros and cons were assessed carefully, followed by various technical reviews and discussions with local authorities and relevant parties.

The foundation for the towers is decided finally to be large size hand-dug caisson, with founding bell-out to sustain the large loads of the superstructure. It is worthy to note that hand-dug caisson foundations, whilst phased out many parts of the world, are standard practice in Chongqing. Pile length varied significantly (7m to 25m), with capacity varying 120000kN to 310000kN. The founding layer is typically moderately decomposed mudstone or sandstone. Typical socketed length of tension piles is 5m. To enable the hand-dug caisson construction, necessary waterstop curtains shall be installed around the site. Other health and safety measures shall also be taken. The cross-section of the hand-dug caissons varied, and is either circular or irregular in shape. The largest hand-dug caissons have pile diameters exceeding 5m with bell-out diameter exceeding 9m. These will be the largest hand-dug caisson for building projects in Chongqing. The podium and basement are supported on a mix use of hand-dug caissons, machined bored piles and shallow footings. Figure 15 below is a foundation plan of the north tower (using hand-dug caissons).

Tender and Construction

Construction has commenced on the site, with major piling works (hand-dug caissons) under progress at the time of the writing of this paper. As part of the design services, Arup is providing full time site service to enhance Jianli's supervision works and to act in the key role of technical advisor on site to solve various site issues for every party.

The tendering works for this landmark project has been a major feat. Arup assisted the Client in the tender preparations, prequalifications, and technical assessments. There were a total of nine tenderers competing for the Main Contractor contract. After over half a year of intensive assessment and follow up, China State Construction Engineering Co. has been awarded the contract and site works. The topping out of the 350m north towers is targeted on October 2017.

The assembly, installation and construction of the conservatory are a major challenge to be faced in this project, amongst the many other challenges and complexities. There are some similarities and case studies with other projects of such nature, the closest perhaps being the Marina Bay Sands development in Singapore, which was also an Arup designed project. It is believed that the conservatory installation method shall be a pioneer in China.

Conclusion

The Raffles City in Chongqing is a one of its kind development. The scale and architectural typology is almost describable as a mini-skyscraper city within a development. The design and construction of the structure of this mini-city has called for innovative approaches and major technical break-through. Some of the most notable technical ingenuities include the hybrid outrigger, (for which a new patent has been approved), the conservatory structure and its articulation, the very long basement box without movement joints, and the economical solution for the curved towers in the development.