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Crown Sydney: An Engineered Response to Sculptural Form

悉尼之冠：对雕塑的工程解读

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Brad Nichols是Robert Bird & Partners Ltd公司的项目主管。2009年从新西兰昆士兰大学毕业后，Brad最初在Holmes Consulting Group公司工作了两年。此后Brad迁至伦敦并于2011年加入了Robert Bird Group (RBG)。在Robert Bird Group 工作期间，Brad参与了若干高层建筑的结构设计。其中最值得一提的是悉尼之冠和伦敦尖塔项目。他的专业领域在于垂直构件差异轴向变形，施工方式以及受场地限制的深基础设计。Brad最近参与的项目包括维多利亚新星，悉尼之冠和伦敦尖塔项目。

Abstract | 摘要

Crown Sydney will be located within Barangaroo South – one of three precincts on the foreshore of Darling Harbour – on the western edge of Sydney's central business district. The project includes a six-star hotel, VIP gaming facilities, luxury retail, and some of the most desirable residential apartments in Australia, taking in views of the Sydney Opera House and Harbour Bridge. The architecture of the tower has a twisting and tapering sculptural form that seeks to maximize the views. The structure is sympathetic to the twisting form, with the perimeter columns following the curvature of the façade. Located on a disused wharf and container storage area, the tower is situated approximately 25 meters from the waterfront. The challenges of site geology and location have informed the selection of the construction methodology which in turn, has influenced the structural design.

Keywords: Composite, Construction, Damping, Foundation, Residential, Structural Engineering

悉尼之冠：对雕塑的工程解读 悉尼之冠开发项目将修建于位于悉尼达令港的巴闌加鲁南部，悉尼CBD的最西侧。此项目面向悉尼歌剧院和悉尼港湾大桥，包括一座六星级酒店，VIP游乐设施，奢侈品零售和澳大利亚最受欢迎的公寓。 整座建筑物的外形呈现旋转状的锥形形态，象一座雕塑，力求最大程度的将悉尼歌剧院呈现在用户的视野之中。建筑的结构依从于螺旋状的外形，周边的结构柱顺着幕墙的弧度和扭转而设置。 本项目所在场地原是一座废弃的码头和集装箱存放区，距海滨仅25米。场地位置和地质的难度将影响到施工方式的选择，而施工方式的不同亦将影响到结构的设计。

关键词：综合、施工、阻尼、基础、住宅、结构工程

Introduction

During the historic expansion of Sydney, the natural attributes of the harbor meant the waterfront was prime real estate for facilitating economic growth in providing easy access to the world; Sydney flourished and grew to become a world-class city. Central Sydney continues to expand, yet it is physically constrained by the harbor and the existing central business district (CBD). To allow for future growth, new opportunities for development are necessary.

Arguably, new development has been occurring for many decades, with waterfront areas that previously held pre-eminence as trade gateways being transformed into residential and leisure playgrounds. The Crown Sydney project, a 71-story hotel and residential development located in Barangaroo South, forms part of this continuing urban renewal of the Sydney waterfront.

Creating such places on constrained inner city sites requires an approach that embraces the challenges as thought provoking, rather than mere obstacles. This allows the

引言

在悉尼城市开发扩展的历史中，港口的天然特性意味着其沿海岸线开发的地产因为整个城市的经济发展提供了与世界连接的通道而被视为黄金地段。悉尼因此逐渐繁荣发展成为国际化都市。悉尼内城的发展因在地理位置上受限于港口及现有的中心商业区则相对滞后。城市需要崭新的机遇才能谋求进一步发展。

可以说在过去的几十年发展中，滨海区由过去杰出的贸易门户，被逐渐改造成公寓及休闲游乐场。悉尼之冠是位于南巴闌加鲁的一座71层楼高的酒店和公寓发展项目，成为悉尼海滨的持续城市更新的一部分。

在内城区兴建类似的项目，需要的是以开创的思维接受种种挑战而不是停滞不前，以探索和革新思想为工程提供解决方案。悉尼之冠项目的限制条件包括靠近海滨，现场地质特点和拟建地下室与邻近已建地下室的整合。建筑的雕塑般外形和建筑体量的特点，则更给设计提出了新的挑战（图1）。本文阐述了本开发项目的结构设计中针对施工和建筑构想的种种挑战的解决方案。

Figure 1. Architectural image of Crown Sydney and the Barangaroo redevelopment (Source: Wilkinson Eyre Architects)
图1. 悉尼之冠和巴阑加鲁开发区建筑效果图（来源：Wilkinson Eyre Architects）

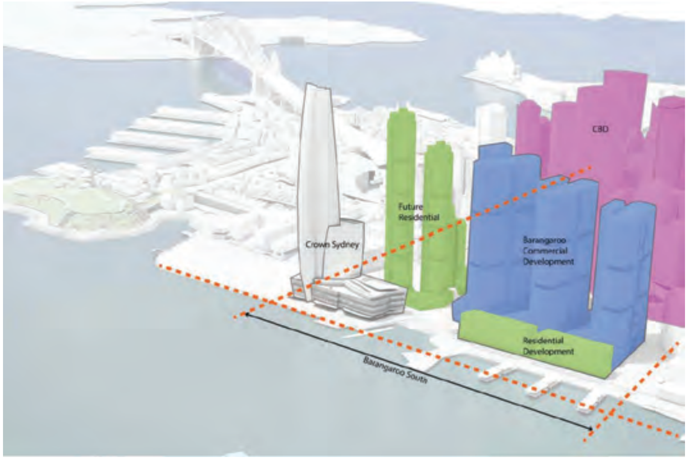

Figure 2. Architectural site view of Crown Sydney and the Barangaroo redevelopment (Source: Wilkinson Eyre Architects)
图2. 悉尼之冠和巴阑加鲁开发区场地图（来源：Wilkinson Eyre Architects）

exploration and evolution of ideas to produce engineering solutions. The constraints of the Crown Sydney project include its proximity to the waterfront, the site geology, and the future integration of the basement with a neighboring site. Additionally, the sculptural nature of the structure and the reduction of its footprint have presented their own challenges (Figure 1). This paper illustrates the structural solutions for both the architectural and construction challenges of this development.

Site

The tower is located approximately 25 meters from the waterfront on the site of a disused wharf and container storage facility (Figure 2). The previous facility was built up to provide a level area suitable for a container wharf. The made ground is contained by the existing harbor wall; therefore, the site geology consists of the made ground and alluvial material over sandstone that dips towards the harbor. The rock depth varies across the site from 18 meters to 33 meters below ground (Figure 3).

The new building footprint is contained inshore of the existing harbor wall. The development will share its basement car park with the proposed residential buildings on the neighboring site; however, the legal boundary between the sites bisects the combined basement. This creates a situation where the harbor side of the Crown Sydney site must retain the lateral earth and hydrostatic pressure for the full basement depth whereas the inshore side of the site does not. This creates an out-of-balance (OOB) loading that drove the foundation solution. The magnitude of the OOB was more than double the base shear from tower wind loading, and was present from the start of the construction sequence.

场地

本结构位于距海滨仅25米的一座废弃码头和集装箱堆放地（图2）。原有场地为适合使用为集装箱码头被建成一块平整的场地。人工填土由已建的港口岸壁支护。场地地质由人工填土，冲积物和之下一直倾斜延伸到港口的砂岩曾组成。场地范围内岩石层则分布于地下18米至33米深，如图3所示（图3）。

拟建结构的边界为已建的近海岸港口墙。本开发项目的地下室可做为地上公寓以及相临建筑的停车场地，建筑红线由地下室中间穿过。这造成了地下的侧向土压力和水压力完全由悉尼之冠项目一侧的地下结构承担而相邻建筑一侧则不需要考虑的状况。这使得地下室外墙的受力不能达到自平衡。本项目地下室的这种不平衡受力状况是基础设计中重点考虑的方面。此不平衡侧力的大小比地上结构所承受风荷载的两倍还多而且在施工开始就一直存在。

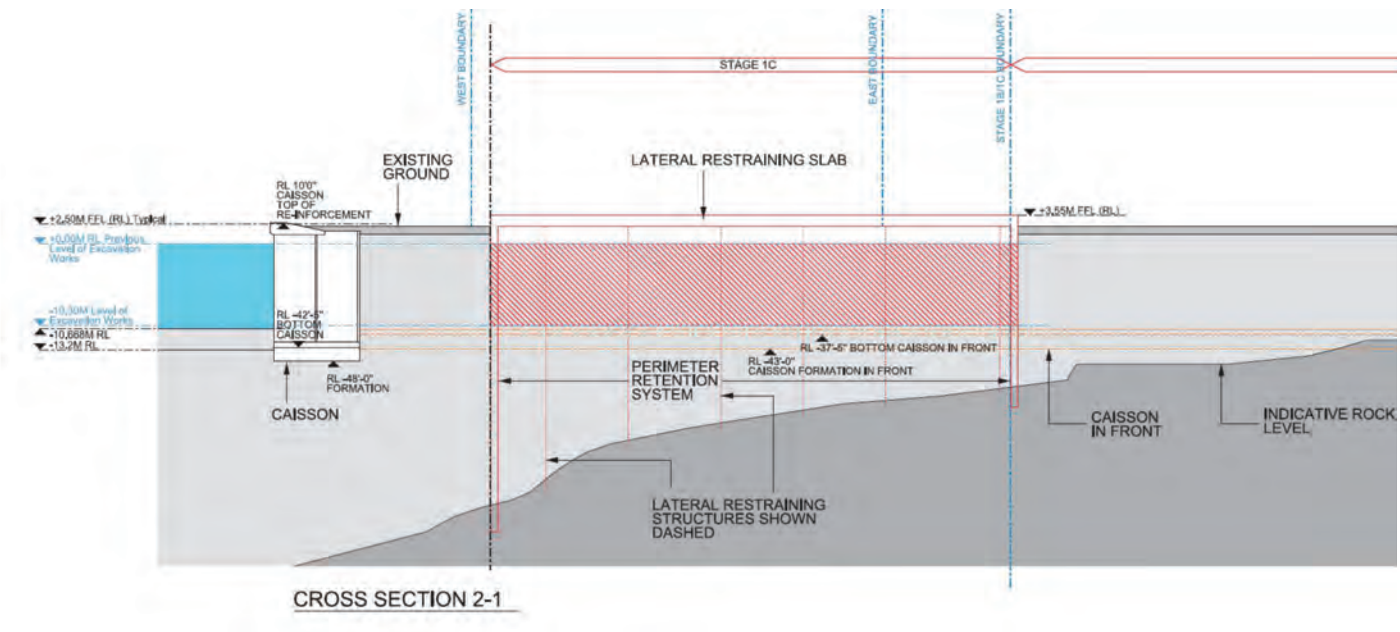

Figure 3. Section through Crown Sydney substructure (Source: Wilkinson Eyre Architects)
图3. 悉尼之冠地下结构剖面（来源：Wilkinson Eyre Architects）

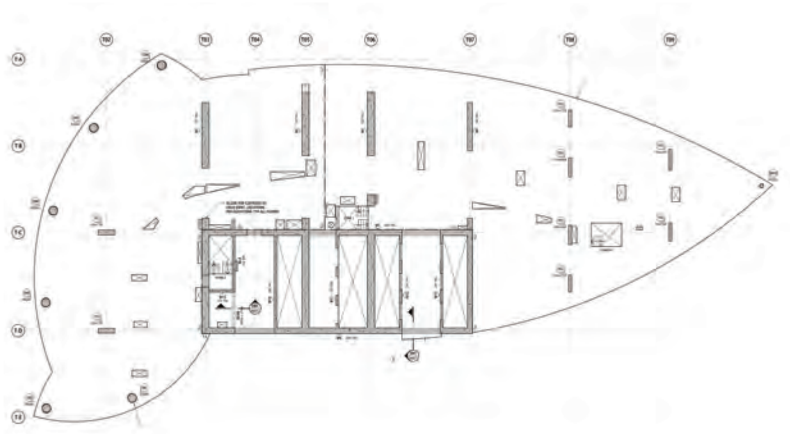

Figure 4. Typical structural plan up to level 24 (Source: Robert Bird Group)
图4. 24层及以下标准结构平面（来源：Robert Bird Group）

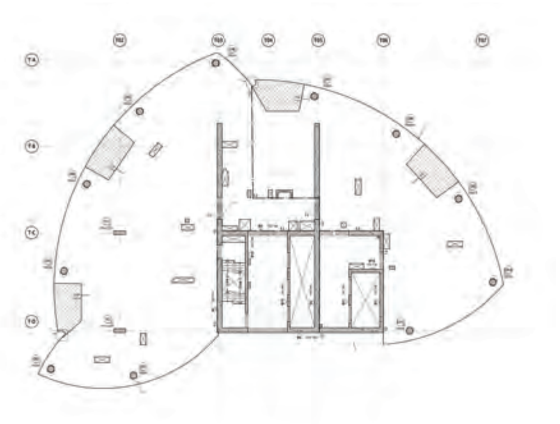

Figure 5. Typical structural plan up to the roof (Source: Robert Bird Group)
图5. 26层及以上标准结构平面（来源：Robert Bird Group）

Figure 6. 3-D view of the tower (Source: Robert Bird Group)
图6. 结构地上主体和地下结构分析3维模型（来源：Robert Bird Group）

Description

The new building comprises three basement levels that extend approximately 15 meters below the existing ground level and across the full footprint of the site. The tower is 71 stories above ground with a total height (to the last occupied floor) of 260 meters. Retail, hotel, and gaming facilities are located in the podium building attached to the main tower. Figures 4 and 5 show the typical building footprint up to the 24th level and the roof, respectively (Figures 4 &5).

The tower has a twisting, tapering form; Figure 6 is an extract from the structural Revit model that illustrates the structure's architectural expression (Figure 6). The floor slabs are 250-millimeter-thick, post-tensioned flat plates supported by the columns and core walls. The perimeter columns follow the twist and taper of the tower, while internal columns were required to keep slab spans manageable for the adopted thickness. TC1 and TC2 are the two main internal columns, and the service core is eccentrically located. Buttress walls are aligned to the primary core walls and help provide lateral stability to the tower. A 200–metric-ton tuned mass damper is provided at the 70th floor to minimize acceleration perception at the top of the tower.

The core wall thickness varies from 750 millimeters at ground level to 350 millimeters at the top. The buttress walls match the core wall thicknesses and are linked to the main shear core by embedded steel or reinforced concrete coupling beams. The depth of the coupling elements varies depending on the location in the tower. The buttress walls clear span approximately 13 meters over the porte cochere at ground level. The walls are supported by the main core and composite, concrete-filled steel box columns.

The perimeter basement wall is a 1,200-millimeter-thick diaphragm wall

结构概述

本项目地下结构包含三层地下室，总深度为场地地面以下15米左右，涵盖整个场地红线范围。地上结构共71层，总高260米。零售，酒店和游乐设施设置在塔楼的裙房。图4和图5分别为24层以下标准层及屋面平面图（图4、5）。

塔楼呈现扭转的锥形形状。图6为结构Revit模型展示的塔楼三维图（图6）。结构楼板为由柱和中筒支撑的250毫米厚后张预应力混凝土板。外围柱依从建筑扭转锥形的外形设置，内柱的设置则是为了依据结构需要减小楼板跨度。两种主要的内柱为TC1和TC2。机电筒为偏心设置。由中筒周边的墙延伸出来伸臂墙以提高结构的侧向稳定。在第70层设置200吨的阻尼器以减低顶部加速度。

中筒的墙厚由地面层750毫米随高度逐渐减薄到顶层350毫米。伸臂墙与中筒周边墙同厚，且由钢筋混凝土或增设钢骨的连梁与中筒连接。连梁的高度根据其所在的位置而不同。伸臂墙在地面层的净跨度为13米，由中筒以及钢骨或钢管混凝土柱支承。

地下室外墙为1200毫米厚的插入砂岩层的地下连续墙。地下一层及地下二层用作停车，以及后勤设施分别为常规的450毫米和220毫米厚的钢筋混凝土楼板承重。地下室最底层为1200毫米厚的钢筋混凝土筏板以抵抗向上水头压力。

主体结构的基础由一系列直径1800毫米的灌注桩以承载结构柱下的荷载，而中筒的荷载由其下厚度从800毫米至1500毫米的墙基础承担。灌注桩和墙基础从地面高度开始施工，基础底部埋入砂岩层。灌注桩和墙基础平面布置如图6所示。

核心筒的结构墙体位于墙基础之上，墙体的荷载通过在地面层设置2500毫米深的环梁传递至墙基础。这道环梁将独立的墙基础联结为一体共同承担核心筒荷载（图7）。

socketed into sandstone. Basement floors one and two are made up of conventional, suspended reinforced concrete slabs of 450 millimeters thick and 220 millimeters thick, respectively, to accommodate car parking and some back of house facilities. The lowest basement level is a 1,200-millimeter-deep reinforced concrete raft slab, sized primarily to resist hydrostatic uplift pressures.

The foundation system for the tower is a combination of isolated large diameter (1,800-millimeter) bored piles, supporting columns, and barrettes varying in thickness from 800 to 1,500 millimeters and supporting the tower core. The bored piles and barrettes are installed from the ground level, and are socketed into the sandstone. Figure 6 shows a plan of the foundation arrangement of piles and barrettes under the tower.

The core walls are located over the barrettes, and a 2,500-millimeter-deep ring beam at the ground level acts as a transitioning element between the barrettes and the walls. The ring beam is designed to link the individual barrettes so that they act as a unit and not as individual elements (Figure 7).

All column and core loads are resisted by the piles and barrettes. The sloping rock profile means that foundations closer to the waterfront are deeper than the inshore foundations.

Construction Method

The proximity to the waterfront, the dipping rock profile, and the presence of the existing harbor wall precludes the use of temporary rock anchors to provide temporary stability to the basement walls during excavation. Therefore, the basement construction solution is a choice between an internally braced, blue sky methodology or a top-down methodology.

The blue sky method is well understood and often the preference when the temporary support of the basement walls can be achieved with temporary rock or ground anchors. This allows an open, easily accessible site for the construction of the permanent structure. It is less attractive when internal strutting and bracing becomes necessary, as these place logistical constraints on the construction of the new permanent structure. In these situations, a top-down methodology starts to become more attractive.

The top-down method also presents an opportunity to accelerate the construction program by creating two work fronts. One work front is the excavation down to formation level, and the second work front is construction above ground. Such a sequence may be called a top-down, top-up method. This can be taken a step further to add in a "jump start" of the central core. The overall program benefit of pursuing a non-linear work flow is significant.

The construction materials and methods are fundamental inputs to the structural design of any project; however, when a top-down method is adopted, this heavily influences the design of various elements. Basement columns and slabs in particular are required to perform functions unique to the methodology during the early stages of construction. Adding an early start to the core construction adds another layer of complexity to the structural design. This, though a proven methodology, presented an unusual situation considering the out-of-balance earth pressure.

Top-down construction relies on the floor slabs and the columns supporting the slabs to be in place before excavation commences. As the excavation progresses, the lateral forces on the walls are transferred through the slabs to the return walls and any vertical elements that have been constructed. As with any structure, as load is applied, the structure moves – this must be considered in the design elements. If the lateral loads are balanced around the site, then these movements can be comfortably accommodated.

For this project, however, the loads are not balanced, so the columns and walls supporting the slabs experience much greater movements. The basement walls and the

所有柱和核心筒的荷载由桩和承载。依据岩石层的分布形态，临近海滨的一侧的基础将比另一侧更深。

施工方法

由于本项目临近海滨，岩石层逐步下沉的分布以及现有港口墙等因素的存在，都阻碍了采用临时锚以在开挖过程中临时固定地下室墙的可能。地下结构的施工方法因此可以考虑顺作法并以内部临时支撑或逆作法两种方案。

顺作法施工非常普遍而且一般是在可由临时岩锚或地锚作为地下室外墙临时支撑的情况下优先考虑的施工方法。明挖顺作法可以为施工提供开敞，方便的施工作业场地。但是当需要设置内部临时支撑时将会对施工场地内物流带来诸多约束。在这种情况下，逆作法可能将是更好的选择。

采用逆作法施工，可以有两个工作面同时操作，为加速施工进度提供了可能。一个工作面是从地面开挖至基础深度，另一个工作面是地面以上主体结构的施工。这样的施工顺序可以称为半逆作法。在此基础之上还可以进一步采用‘跳作’法提前核心筒的施工。因此，整体施工进度将会大幅度提高。

施工的方法和材料对于任何项目的结构设计来说都是至关重要的因素。然而当采用逆作法施工时，其对于结构设计例如地下室楼板和柱的影响将尤其明显。这些地下室楼板和柱将在早期施工过程中起到作用。将核心筒的施工进一步提前将使得结构设计变得更加复杂。根据以往的工程经验，逆作法是一种可行的施工方法，然而不平衡的土压力是本工程需要特殊考虑的因素。

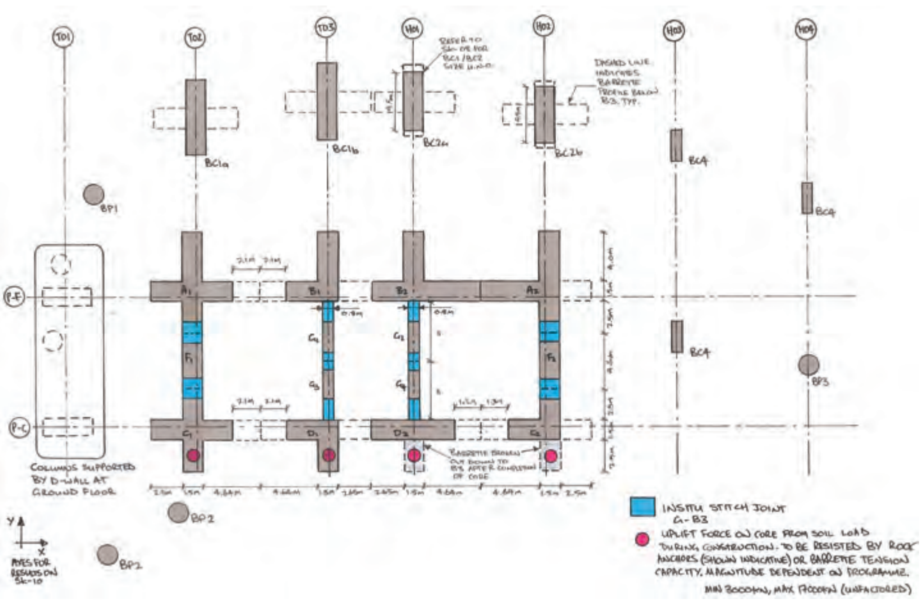

Figure 7. Barrette layout under the core and tower columns (Source: Robert Bird Group)
图7. 柱和核心筒下墙基础布置（来源：Robert Bird Group）

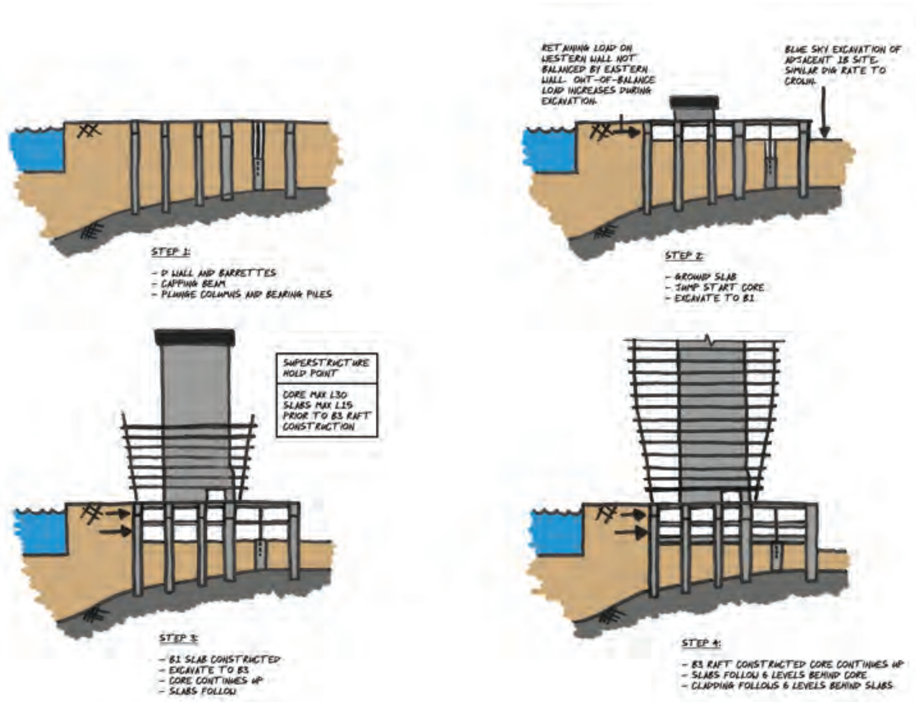

Figure 8. Top-down, top-up sequence diagrams (Source: Robert Bird Group)
图8. 半逆作法施工顺序图（来源：Robert Bird Group）

core barrettes provide the resistance to the lateral earth and hydrostatic pressures. The movement cannot be eliminated; it therefore induces permanent eccentricities between the founding level and the future permanent columns and walls above ground. These eccentricities induce additional secondary design actions which would not have normally been present. The magnitude of movement is in the order of 50 millimeters.

There is no question that adopting such a methodology adds complexity to the design and material cost, however this is offset by the reduction in time to complete the project. Figure 8 shows the proposed construction sequence and the proposed program is summarized in Figure 9 (Figures 8 & 9). It can be seen that the core construction is expected to commence just one month after the excavation operation begins. The tower superstructure is expected to commence well before the excavation operation is complete (Lend Lease, 2015). Arguably, if a conventional, linear construction sequence was followed, the core and tower superstructure could not be started until the lowest basement had been constructed.

Tower Design

The challenges for the structural design of the tower were primarily focused around serviceability performance.

The architectural form can be loosely described as an extrusion that rotates about the vertical axis. The rotation opens up views of the Harbour Bridge and the Opera House to more apartments than if the tower was simply vertical. There was a strong desire for the tower to twist and for the structural solution to respond to the architecture. The client saw the advantages of this, and embraced this ethos; from early in the design process, it was established as a core principle.

逆作法施工开挖前，需要提前将柱和楼板施工完成。在开挖过程中地下室墙承受的水平力将由楼板传递到墙或其他施工完成的竖向构件。任何结构都会在荷载作用下产生移位和变形，这是在结构和构件设计中必须考虑的。而当场地地下结构侧向力可以达到自平衡时，因此产生的移位的问题将很容易解决。

但是对于本项目来说，地下水平力是不能自平衡的，故而承托楼板的墙，柱将会产生明显的变形。侧向土压力和水压力由地下室墙和桩抵抗。这些地下竖向构件的变形不能被消除，并且会因此在结构的基底和地上的墙柱之间产生持久的偏心作用。这种偏心作用将给结构带来二阶结构作用。根据分析这种侧向变形的大小大约在50毫米左右。

采用逆作法这样的施工方法无疑将带来结构设计的复杂性和结构材料用量的提高，但同时却可大幅度提高施工进度。施工顺序如图8所示，施工进度计划如图9所示（图8、9）。从图中可以看出，核心筒的施工在开挖开始后一个月就可以开展。地上主体结构则可以在开挖完成前很久就可以开始。如果是采用顺做法施工，核心筒和地上主体结构必须要在最底层地下室开始施工后才可以开始。

主体结构设计

主体结构设计的挑战主要集中在结构耐用性能控制上。

建筑外形大体上可以认为是围绕竖向中心旋转而上。这种旋转开阔了视野，把悉尼歌剧院和悉尼大桥都收入大部分公寓的景观之中。这种旋转是建筑设计对结构设计的一个重要要求之一（如图9所示）。这也是开发商非常希望达成的销售效果。因此观景效果自设计工作伊始便成为主要设计理念之一。

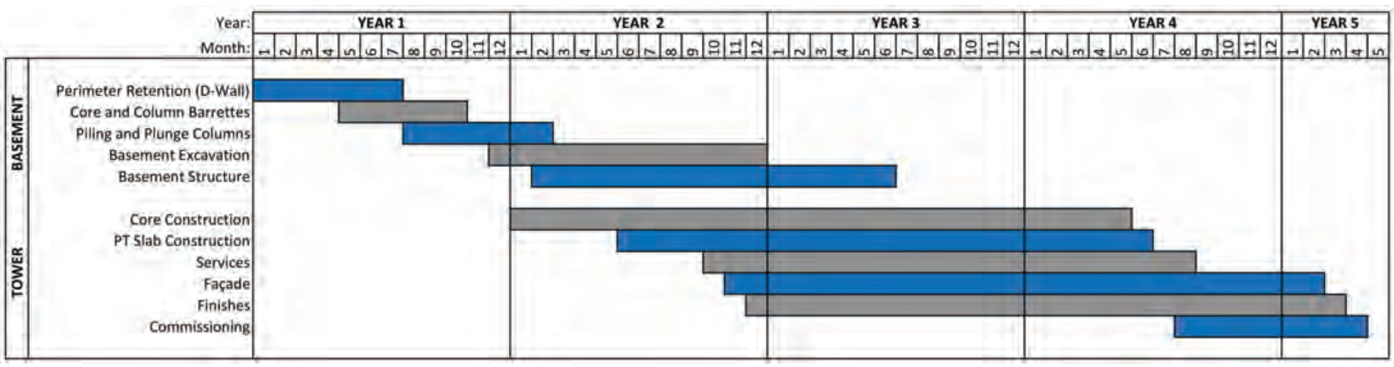

Figure 9. Summary of key stages in the construction program (Source: Lend Lease)
图9. 核心阶段施工组织图（来源：Lend Lease）

Lateral Load Resisting System

The lateral system for the tower is fairly conventional with a reinforced concrete core buttressed by shear walls. At the concept stage there was uncertainty regarding the performance of the tower under wind loads. The eccentricity between the center of stiffness and of mass of the tower, coupled with the twisting structural form, gave rise to such uncertainty. There was concern that the natural tendency of the tower to twist may result in torsion being coupled to the translation modes. To give confidence in the lateral performance, engagement of the wind consultant early in the process was essential.

During the development of the structural concept and after receiving initial advice from the wind consultant, it was clear that drift control and occupancy comfort were the most critical design criteria. The drift control was particularly relevant for the façade design. Additional inter-story movement due to the twisting profile added to the complexity of the project, particularly with respect to the serviceability performance for the façade; however, the occupancy comfort criterion proved significantly more challenging to meet.

Improving the performance of a tower can be achieved by manipulating the mass distribution, stiffness, and damping. A number of options that attempted to stiffen the building, like adding wall thickness and introducing outriggers, were investigated, but none of these solutions were found to be particularly efficient or elegant. Their impact on saleable area was unpalatable and reduced the value of apartments in the most desirable floors of the tower.

Adding mass to the top third of a building is sometimes an efficient method of improving dynamic performance with respect to occupancy comfort; however, this has a downside when seismic loads are considered, as additional mass generally results in higher design actions for the seismic case. The coupling beams were already highly stressed under the seismic design case and therefore, this was also not considered a desirable solution.

In parallel, an alternative solution to introduce supplementary damping was investigated. Some of the options considered were a tuned mass damper and a tuned liquid damper. The space requirement for the tuned liquid damper would have resulted in significantly compromised space at the top of the building where the penthouse is located. The alternative tuned mass damper solution was therefore selected, and is located on the 70th level. Its location was selected in a position found to have the least impact on apartment space.

The final solution is a combination of stiffening and supplementary damping. The damping is primarily added to meet the occupancy comfort criterion, while stiffening the lateral system has the greatest benefit in meeting the drift criterion associated with the façade design. At the time of writing this paper, the idea of using the additional damping to assist with reducing the loads at service levels was also being considered to help meet the drift criterion.

Gravity Load Resisting System

Crown Sydney is a concrete building with slabs supported by columns and walls. There are two groups of columns: perimeter and internal. The perimeter columns follow the twisting shape of the building. To minimize architectural impact, all columns throughout the tower were originally designed as composite concrete-filled steel sections. The columns were later changed to larger conventional reinforced concrete sections, as the cost and program savings were the most beneficial.

A primary concern was the potential impact of the twisting profile of the perimeter columns. To create the twist, the columns are not vertical, but instead, slope; this induces a permanent horizontal reaction at each floor level, and since the columns all slope in the same direction around the tower, the result is torsion under gravity loads.

The initial thought was to design a vertical structure that could fit inside the twisting profile to eliminate torsion, but this would mean that the columns would be in different positions relative to the apartment demise walls on each level, resulting in more apartment types to be designed. Ultimately, this approach did not respect the core principle of the twisting tower.

During the concept development, the impact of the sloping columns was investigated to understand the magnitude of the loads and what this may have meant for the structural design. Early simplified studies of the structure showed that the twist was more benign than first instincts suggested. It was found that the effect of the axial shortening of the columns along the length of the axes created a small counter torsion that helped to reduce the effect of the sloping columns.

侧向抗力体系

本项目的侧向结构体系为常规的钢筋混凝土核心筒辅以伸臂剪力墙。在概念设计阶段，塔楼在风荷载作用下的反应还不完全确定。结构质量中心和刚度中心之间的偏离以及结构旋转的外形更增加了受力反应的复杂性。结构扭转的自然趋势会增加扭转振型效应。为明确掌握结构侧向受力特性，在设计早期风动顾问的参与，建议十分必要。

结构概念设计阶段中，在风动顾问的建议下，明确了结构侧向变形和舒适度控制为设计的主要指标。结构的侧向变形与幕墙的设计紧密联系。由于旋转外形带来的附加层间位移使得为幕墙耐用性能设计更加复杂。

结构抗侧力性能的提高可以通过调整质量，刚度及阻尼的分布达成。在设计过程中曾尝试采用不同方式，比如增加结构墙的厚度以及引入伸臂行架等。然而结果显示上面两种方案的效果并不理想。而其对于可销售面积及价值最高的楼层的高端公寓的影响却是不得不考虑的。

在一些案例中，增加顶部三分之一高度内的结构质量会是提高结构动力性能尤其是舒适性的有效措施。然而这种方案的缺陷是在地震作用下，顶部增加的质量会增加设计地震荷载。在抗震设计中给已经处于高应力状态的连梁设计带来更大难度，故这也不是理想的解决方案。

设计中亦研究了在结构中设置阻尼器的方案。其中有质量减震器和液体减震器两种选择。液体阻尼器对放置空间的要求会大量占用建筑物顶部阁楼层的面积。而质量阻尼器对公寓的面积影响则小得多。

最终结构设计方案是综合考虑以上各种方案，采取了增强结构刚度及采用阻尼器的组合。阻尼器的设置主要是为了解决舒适性的问题而侧向刚度增加是为了满足幕墙变形的要求。至撰写本文时，考虑在设备层设置附加的阻尼器以满足侧向变形要求。

竖向结构体系

悉尼之冠项目为一座混凝土结构，由结构墙和柱承托楼板以抵抗竖向荷载。其中结构柱包括边柱和内柱。边柱依从建筑物外形设置。为把对建筑布局的影响降至最低，所有结构柱最初均设计为钢管混凝土柱。随着设计的展开，考虑到对造价和工期的影响，所有柱均改为常规的钢筋混凝土断面。

在设计中首先需要考虑的是旋转外形对边柱设计的影响。为实现旋转的效果，柱身

The twisting effect was not eliminated; however, it was felt that it could be managed more effectively. It was clear that a detailed construction stage analysis would be required to more accurately predict likely movements.

Time Dependent Movements

In tall buildings, the effects of time dependent concrete properties (creep and shrinkage) compound over many floors. Issues may occur due to differential axial shortening, where adjacent vertical elements (columns, cores, and walls), shorten by different amounts. As the vertical elements shorten, the connecting slabs and the elements they support (cladding and finishes) must also move. If the differential movement is too great, the induced slab curvature may create serviceability issues, such as damage to cladding and finishes. Differential axial shortening is often not evident at the start of a building's service life, but may lead to a legacy of maintenance issues.

The change from the original composite columns to reinforced concrete columns changed the time dependent behavior of the building. This was due to two components of concrete behavior; shrinkage (volume change due to moisture leaving the concrete) and creep (volume change over time under an applied load). In a concrete-filled tube, there is no path for water within the concrete to escape, so shrinkage becomes negligible and creep reduces (Han, Tao, and Liu, 2004). These effects are significant for reinforced concrete columns, and to compensate for the change in column type, the column cross sectional area was increased by an average 30 percent during the redesign.

A non-linear construction stage analysis was carried out to estimate time dependent movements, both vertical (axial shortening) and horizontal (twist), which occur during construction of the tower and continue throughout the life of the building. The model considered all contributing factors including foundation stiffness, sequential application of the basement OOB load, construction program and variation in material properties. Post-processing software was developed to calculate the differential shortening (absolute value and curvature), between all vertical elements at every floor. This information was used to tune column sizes, reinforcement and concrete grade to limit differential shortening to an acceptable range.

Generally in tall buildings with constant distance between columns, shortening issues can be addressed fairly simply; however, on Crown Sydney the twisting and tapering shape of the building meant that the distance between the perimeter and internal columns, and the core changed at each floor. Where the perimeter columns moved close to the two main internal columns – TC1 and TC2 – differential shortening issues could not be overcome by the tuning of columns. "Walking Column" systems were used to move TC1 and TC2 away from the perimeter columns to reduce the induced slab curvature and, in turn, mitigate the impact on finishes (Figure 10).

Figure 11 shows the long-term vertical movements (shortening) of the four types of vertical elements: the core, a full-height perimeter column, a perimeter column supported on the core at the 24th floor, and a

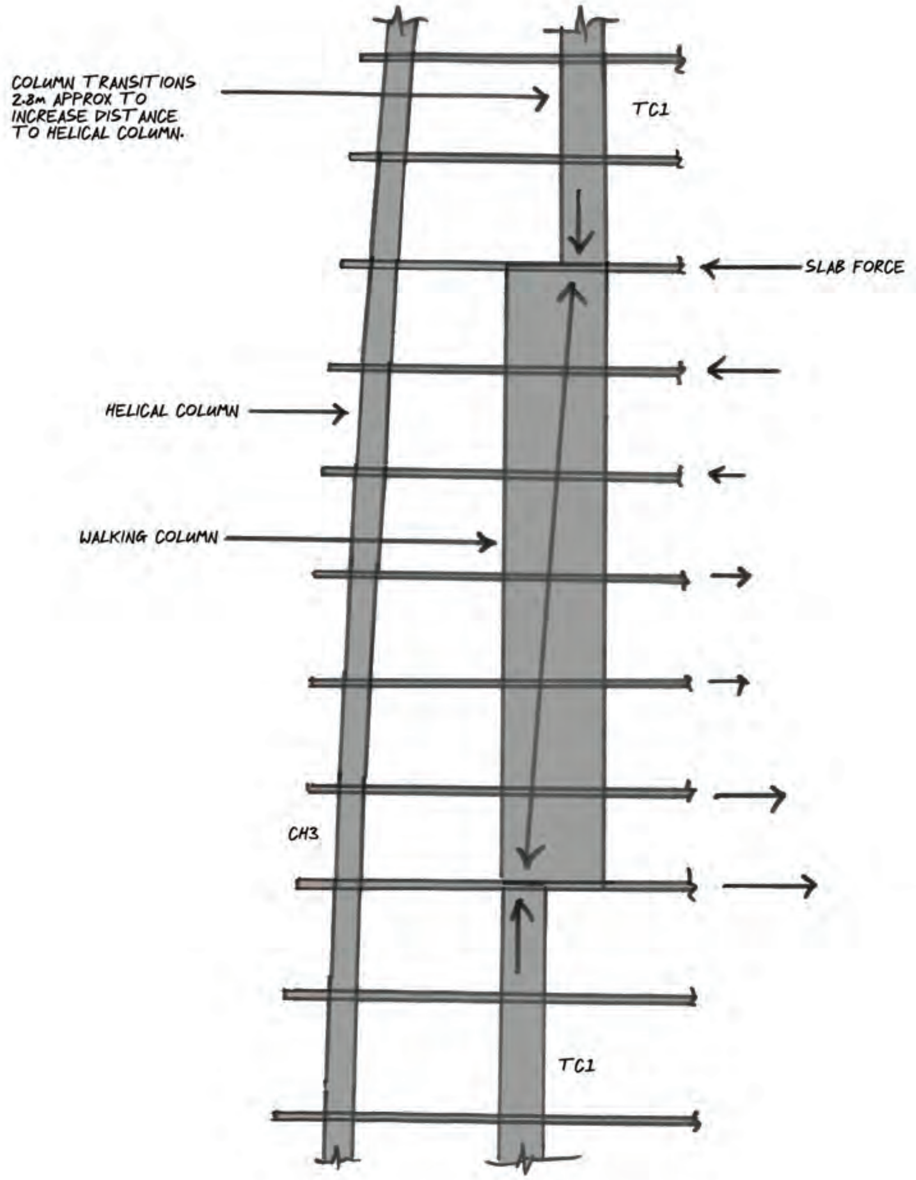

Figure 10. Elevation of a walking column system (Source: Robert Bird Group)
图10. 走柱体系立面（来源：Robert Bird Group）

不再能保持垂直而是需要一定的斜度。斜柱的设置将对各层楼板产生水平作用。所有柱的一致的倾斜方向在重力作用下又对结构整体产生了扭转效应。

最初的设计构想，是考虑在不规则建筑外形内设置适当的垂直结构以避免扭转效应。但是这将意味着对每一层来说，外柱与公寓之间的隔墙的距离均不同。这将使得各层公寓的户型都不尽相同而偏离了本开发项目的主体构想。

在概念设计阶段，通过对以给设计带来的影响进行了研究，对柱倾斜带来的附加荷载及对结构整体的影响有进一步的理解。结构初步分析显示这种扭转比预想的略小。这是因为柱的轴向变形会产生一定的扭转效应，因为其反向于柱倾斜带来的扭转，顾而部分抵消了斜柱的影响。

part-height internal column (Figure 11). Note the different shapes of the shortening graphs.

Figure 12 shows the long-term horizontal movement (twist) at the perimeter of the floor plate for three points: perimeter column close to the core, perimeter column remote from core, and a perimeter column supported on the core at the 24th floor (Figure 12). The core is the center of rotation and hence, points further from the core have larger horizontal displacement.

The core and columns will be pre-set based upon estimated movements up until the end of construction. This does not affect the magnitude of long term movement.

Conclusion

The Crown Sydney project is an example of urban reclamation and regeneration for an area of the Sydney waterfront that had been neglected for some time. The site presented a number of challenges; however, the structural design has been developed to help unlock the potential for the site and create a new retail and leisure precinct. The sculptural form of the new tower adds to the intrigue, and it will hopefully become an immediately recognizable meeting point for the people of Sydney.

The structure is sympathetic to the twisting form, with the perimeter columns following the curvature and twist of the façade. The perimeter columns wrap around the tower and induce a permanent twist on the structure, creating a number of structural challenges, including the need for a prediction of the tower's horizontal and vertical movements, for which a

结构整体扭转的效应依然存在，但是可以被减小到可控范围内。在施工图设计阶段，需要进行更加详尽的分析以准确计算结构的受力和变形。

长期时效变形

在高层结构设计中，混凝土的长期变形（收缩和徐变）将在很多楼层中产生。轴向变形差异带来的问题，是相邻竖向构件（柱，核心筒和其他结构墙）在重力作用下的压缩变形差。当竖向结构构件缩短时，与其相连的楼板及楼板支撑的幕墙和建筑面层会与之一同变形。如果这种差异变形过大，其带来的楼板弯曲变形将会带来诸如建筑面层破坏等结构耐用性的问题。这种轴向变形差异的影响往往在结构交付使用初不会被发觉，然而随着时间推移会逐渐呈现出来并对建筑物的使用和维护带来问题。

结构柱的材料从钢–混凝土组合柱方案至钢筋混凝土方案的修改，改变了建筑物的长期变形特性。这是由于混凝土材质的特性，收缩（因水分随时间的流失而带来的体积变化）和徐变（长期荷载作用下的体积变化）。在钢管混凝土柱在，由于钢管的限制切断了混凝土水分流失的途径所以收缩变得微不足道和蠕变也降低（韩，陶和刘， 2004）。而这些效应在钢筋混凝凝土柱中则相对明显，为补偿这种长期变形，钢筋混凝土柱的横截面面积被重新设计期间平均增加30%。

在设计中进行了非线性施工阶段分析，以估算建筑在施工过程中和长期使用中结构垂直（轴向压缩）和水平（扭转）方向的变形随时间发展。该分析模型考虑了所有影响因素，包括基础刚度，地下室不平衡荷载的持续作用，施工方案和不同材料性能。

后处理软件的开发是为了计算各层所有竖向构件之间的轴向压缩变形差（绝对值和曲率）。据此计算结果调整柱断面尺寸，钢筋和混凝土级别使得压缩变形差限制到可接受的范围内。

通常在高层建筑中，柱距相对规则，差别不大，使得压缩差异的问题相对容易解决。然而悉尼之冠建筑物的扭曲和渐缩形形状意味着在每个楼层改变了周边柱和内柱与核心筒之间的距离都不相同。其中，在外围柱处在与附近的两个主要内柱TC1和TC2时 ，压缩差异的问题就不能用调整柱断面的方式解决。 “走柱”系统的采用将TC1和TC2从移位，增加其与外柱的间距，以减小差异压缩带来的楼板变形弧度，把对建筑面层的影响降到最低（图10） 。

图11示出了四种类型的竖向构件的长期垂直变形（缩短）（图11），包括核心筒，一个全高外围柱，一个支撑在24层的核心筒的外柱和一个部分高内置柱。请注意缩短图中的不同的形状。

图12示显示了沿楼板边缘三个点的长期水平变形（扭转）（图12），这三个点包括一个临近核心筒的边柱，一个远离核心筒的外柱，和一个支撑在24层的核心筒的外柱。由于核心筒是结构整体扭转的中心，因而与核心筒距离更远的具有较大的水平位移。

核心筒和柱的施工定位将根据施工过程中变形的估算预设。这不会影响长期变形的幅度。

结语

在悉尼滨海的一个长期被忽略的区域兴建悉尼之冠项目，为城市回收和再生提供了一个案例。拟建场地存在的诸多挑战，在

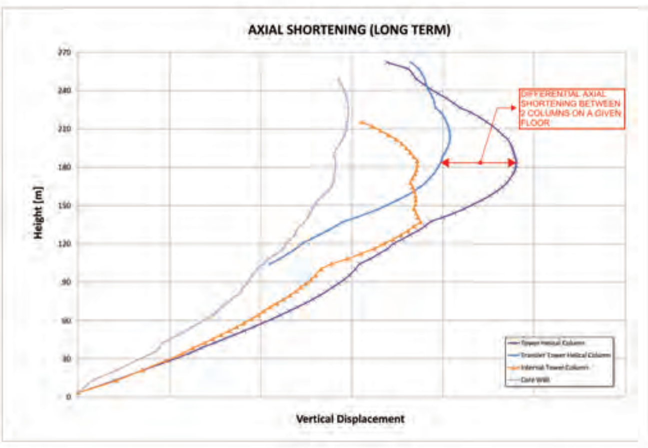

Figure 11. Long-term axial shortening plot for key vertical elements (Source: Robert Bird Group)
图11. 主要垂直构件长期轴向变形图（来源：Robert Bird Group）

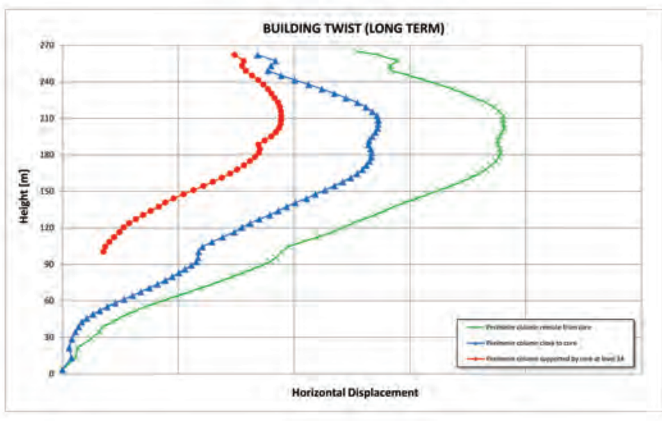

Figure 12. Long-term horizontal movement plot at three points (Source: Robert Bird Group)
图12. 三点长期水平变形图（来源：Robert Bird Group）

comprehensive construction stage analysis was performed. The site constraints of proximity to the waterfront, the presence of the harbor wall, and the dipping rock profile suggested that a top-down construction methodology was appropriate. The out-of-balance earth pressure loads added an additional layer of complexity to the design. The top-down, top-up construction method created an opportunity to accelerate the construction program, as its non-linear workflow allows tower construction to begin soon after the start of basement excavation.

Acknowledgements

This project would not be possible without the architectural inspiration of Wilkinson Eyre Architects nor the vision and support of Crown Resorts to understand and value the unique offering the architectural form presents. We wish to thank our structural engineering partners John A Martin & Associates of Nevada, with particular thanks to Steve Schiller and Jon Toone. The project has been a successful collaboration of many offices and design organizations located in all parts of the globe.

结构设计中被逐一解决，使得在这片场地上创建新的零售和休闲专用区成为可能。

犹如雕塑一般的悉尼之冠一旦建成，将有望立即成为悉尼市民关注的焦点。

结构外柱的设置与幕墙的曲线和旋转外形协调一致。周边柱环绕塔楼设置给结构带来长期的扭转效应。这给结构设计带来一定的难度和挑战，其中包括塔楼整体的水平和竖向弯矩使得施工分析更加复杂。

综合考虑项目拟建场地周边状况的限制包括靠近海岸线，已有港口墙和逐步下沉的岩石层，建议采用逆作法施工。地下室外墙承受的不平衡侧向土压力给设计带来更多的难度。

逆作，半逆作的施工方法可以加速整个施工进度。在这种非线性施工组织安排下，塔楼的施工可以在地下室开挖伊始就可以进行。

致谢

本项目的结构设计是基于建筑师Wilkinson Eyre Architects的建筑设计构想，并在Crown Resorts的支持下达成对项目的理解和对独特建筑形式的设计完成。感谢结构设计合作伙伴 – 位于美国内华达州的John A Martin & Associates公司并特别鸣谢Steve Schiller和Jon Toone的合作。本工程亦为位于世界各地的不同办公室和设计机构的通力合作下的成功作品。

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