Issue 1 2021

ARUP

The Arup Journal

Contents

Ken Rosewall Arena, Sydney, Australia: Martin Mischkulnig

1.

A city in the sky

This landmark development was inspired by old sailing vessels, drawing on Chongqing's status as a gateway to western China

Authors Penny Cheung, Lu-Lu Du, Gary Ge, Antony Ho, Michael Kwok and Allen Sun

Raffles City Chongqing is located at the heart of Chongqing, at the confluence of the Yangtze and Jialing rivers. This strategic position is fitting for this mega-scale development, the design of which was influenced by and serves as a symbol of Chongqing's past as a trading centre and its long-held status as a gateway to western China.

The high-rise complex was designed in collaboration with Safdie Architects and was inspired by historical images of great Chinese sailing vessels on the river. Gently arcing towards the water, the towers form the apex to the city's peninsula, like the masts of a ship, with its sail pulling the city forward.

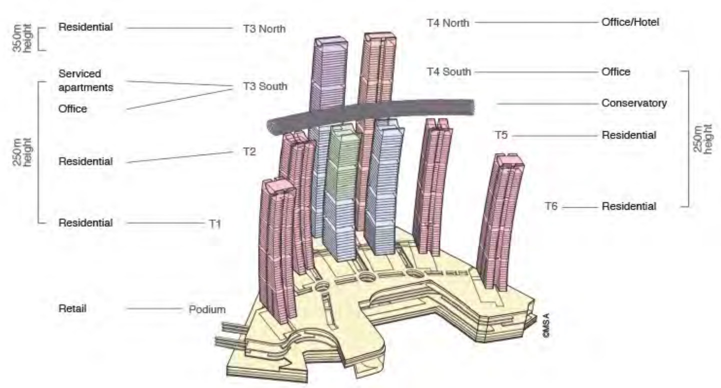
Raffles City Chongqing is a mixed-use development, with a total floor area of 1.13 million m^2. It comprises a shopping mall and eight curved towers – two 350m-tall north towers and six 250m-tall south towers – which house 1,400 residential units, offices, 200 serviced apartments and 450 hotel bedrooms. One of the north towers is fully dedicated to residential use, making it the tallest residential tower in China. The second north tower is office space below the skybridge, with the hotel above.

Six of the towers are linked 250m above ground, with four of the 250m-tall towers capped by the 15,000m^2, 300m-long skybridge, The Crystal, which faces southwards over the city. Two smaller skybridges link it with the two 350m-tall towers. The Crystal brings amenities and

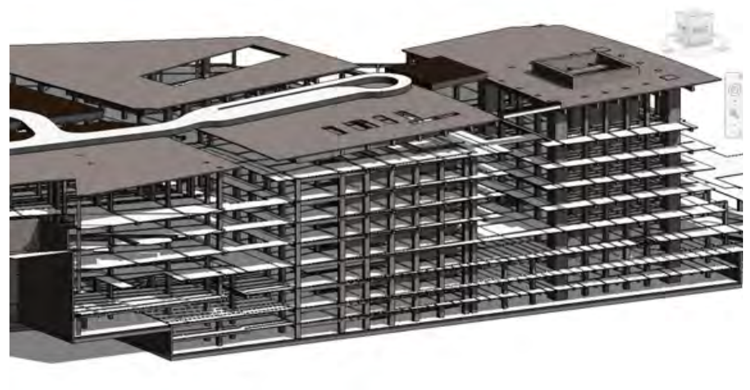
1: Chongqing's past as an important trading centre is reflected in the design of Raffles City Chongqing, which was inspired by historical Chinese sailing vessels

2: The complex sits at the confluence of the Yangtze and Jialing rivers

2.



3.



4.

green space high into the sky, housing the hotel lobby, bars and restaurants, a public observatory, and a clubhouse, swimming pool and gymnasium-type facilities for the residential apartments.

The podium is approximately 400m x 250m on plan and has nine storeys, including three basement levels. On the podium roof there is a landscaped park that consists of 45,000m² of public and private green space. The podium contains 250,000m² of retail space and is an important transportation hub, integrating with the bus and ferry terminals and a subway station; it also provides links to Chaotianmen Square, which overlooks the meeting point of the two rivers.

To design this complex technical project, Arup mobilised resources locally and from around the globe, involving the firm's offices in Beijing, Chongqing, Hong Kong, Shanghai, Tianjin, Ho Chi Minh City, Boston and New York. The firm had worked previously with the client, CapitaLand, on Raffles City Chengdu and Raffles City Hangzhou, and with Safdie Architects on Marina Bay Sands in Singapore, where there is also an elevated skybridge linking to high-rise towers.

Arup provided civil, fire, geotechnical and structural engineering services, along with building sustainability design, for all stages of the project from scheme through to construction.

Designing the slender towers

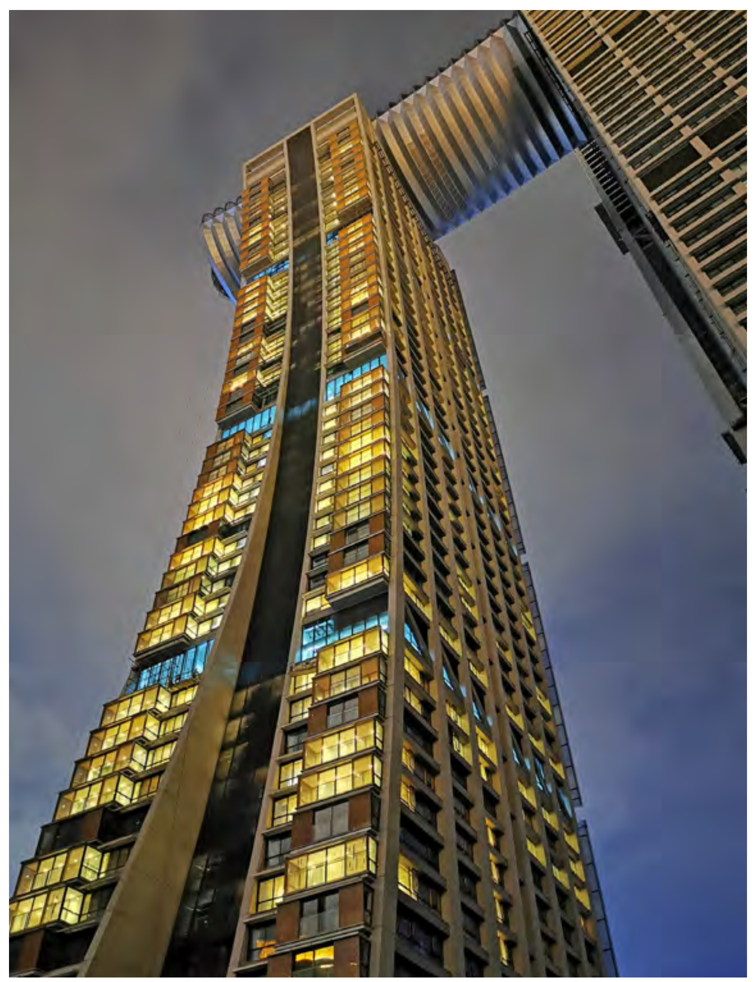
The design of the two 350m-tall north towers was a major challenge for the project team due to the site location (ground conditions are variable, and the position at the confluence of two rivers creates high wind loading) and the towers' high slenderness ratio – each has a footprint of only 38m x 38m, giving a slenderness ratio of 9.4. The Chinese building code recommends a tower slenderness ratio of around 7, and typically most super high-rise buildings have a ratio of up to 8. This added to the complexity of the tower design, which also needed to accommodate the high wind load and earthquake activity in the area. The towers have a reinforced concrete core, with composite concrete and steel floor plates.

Such tall towers usually have a structural system that includes mega-columns and a braced frame. However, the use of bracing would have affected the views from the towers so Arup adopted a stability system without mega-bracing, comprising a reinforced concrete core, four corner mega-columns with belt trusses, a perimeter moment-resisting frame and four levels of hybrid outriggers.

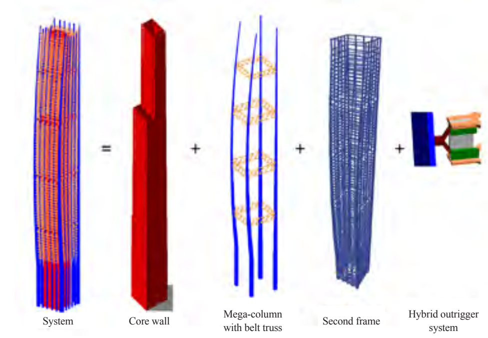
3: The complex contains a hotel, residential and office space, green public areas and a shopping mall

4: The podium consists of nine storeys, including three basement levels. The roof features a landscaped park

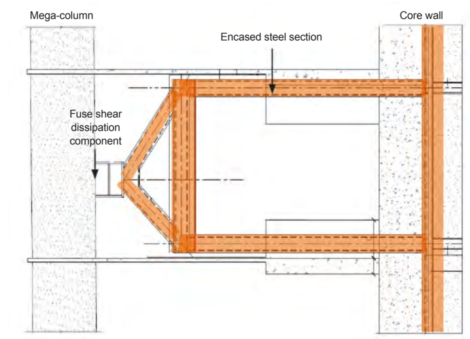
5: The towers arch towards the water like a ship's sails



5.



6.



7.

The outrigger is not a new concept and has been applied to many high-rise buildings around the world. With the belt trusses and outer columns, a conventional outrigger acts as a rigid arm, connecting the building core to the outer columns and providing lateral stability. However, typically it is an expensive system due to the large amounts of steel required, the complex construction methods – especially at the connection joint at the corner of the core wall – and the longer construction time needed.

Arup used an innovative hybrid outrigger system, developed specifically for this project, which uses a structural fuse. This method is suitable for high-rise buildings in moderately seismically active regions like Chongqing. The fuse connects the outrigger wall to the mega-column, controlling the load path during a seismic event. Under normal wind loads and level 1 earthquakes (an expected 100-year return period), the fuse remains fully elastic, acting in the same way as a typical outrigger.

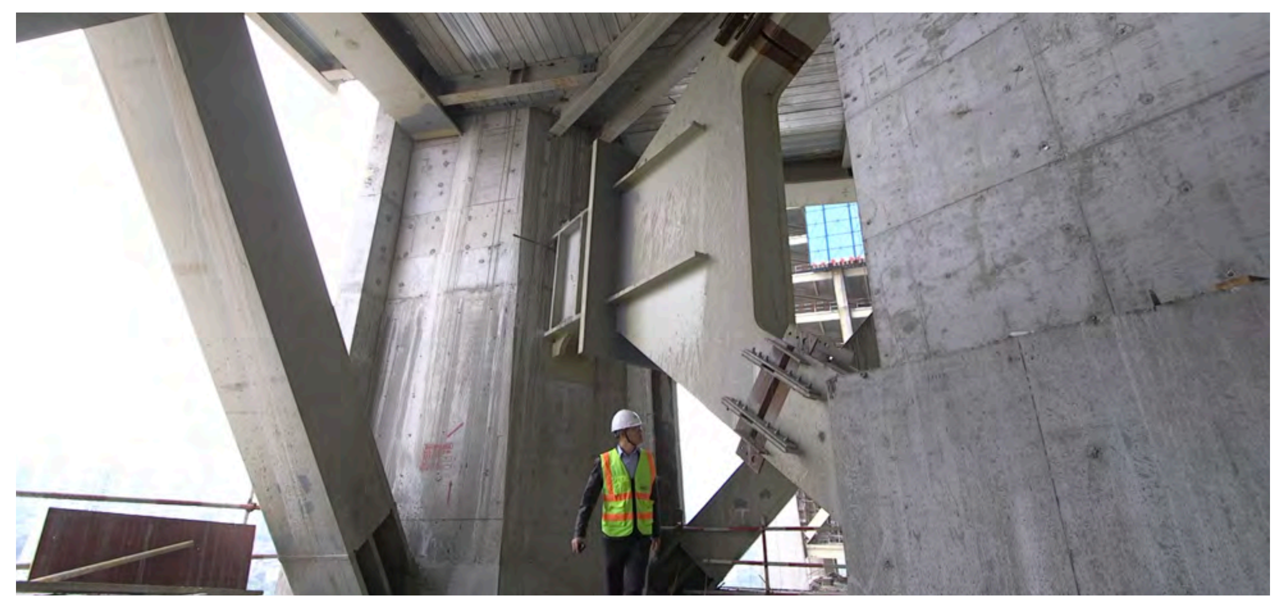
The hybrid outrigger gives a 7% improvement on the towers' lateral stiffness at elastic stage compared with a traditional system. For level 2 and 3 earthquake events, the fuse's shear dissipation component yields and deforms in a controlled way, allowing the energy to dissipate. This damping effect protects the outrigger wall and core wall from damage in severe earthquakes. The fuse can be readily replaced after yielding.

Arup carried out numerous linear and non-linear analyses, even for extreme earthquake levels (higher than required), to justify the structural performance of the system. In addition, a scale-to-scale experiment was carried out to test the reliability of the solution and to confirm the analytical findings.

This new application of a fuse in an eccentric braced frame is a major innovation. Arup received patent approval for this hybrid outrigger wall system and was awarded the China Innovation Award – Honourable Distinction for the design at the China International Exchange Committee for Tall Buildings – Council on Tall Buildings and Urban Habitat (CITAB-CTBUH) China Tall Building Awards.

The system also improves buildability and shortens construction time, creating further cost savings. The hybrid outrigger uses a full-storey-height reinforced concrete wall, with thickened sections top and bottom near the core wall to provide stiffness, thus reducing the quantity of steel required by 10% compared with traditional outrigger systems.

The 250m-tall south towers were mainly constructed with reinforced concrete, with



8.

6: The structural system for the two north towers does not use a braced frame, thereby retaining the views from the towers

7: By connecting the outrigger wall to the mega-column, the fuse can control the load path during seismic events

8: The hybrid outrigger uses a full-storey-height reinforced concrete wall the floor system consisting of a concrete beam and slab frame. The stability system for these towers utilises the concrete core, perimeter moment-resisting frame, belt trusses and a limited number of outrigger trusses supporting the skybridge, which also provide horizontal stability for wind and seismic loads.

Due to the scale and complexity of the project, the design of the hybrid outriggers and elements relating to wind engineering, slope stability, foundation and seismicity design all required approval from expert panel reviews.


11.

9: The Crystal sits atop four of the towers

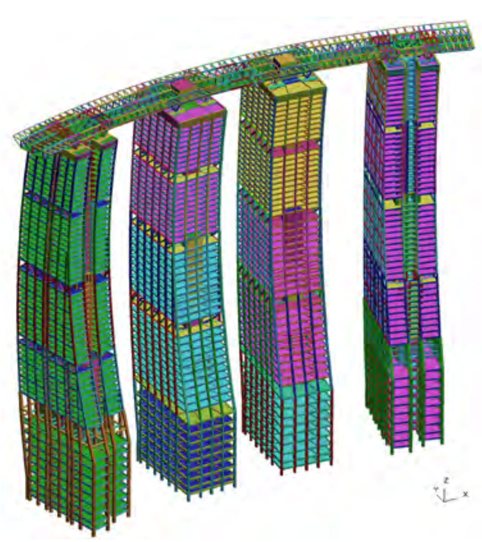
10: An LS-DYNA model was developed to analyse The Crystal's movement in seismic conditions

11: Two smaller skybridges connect The Crystal to the two 350m-tall north towers

Bridging the towers in the sky

The most notable feature of the development, and another major engineering challenge, was the design of The Crystal – the 300m-long, 32m-wide and 26m-tall glass-clad skybridge structure that sits atop four of the 250m-tall curved towers. The Crystal has a maximum span of 54m, with 26.8m end cantilever spans, and was constructed using 11,000 tonnes of steelwork.


9.


10.

While the development bears a resemblance to the 200m-tall Marina Bay Sands in Singapore, Raffles City Chongqing has very different design conditions. It has taller and more slender towers, is located in a more active seismic zone and has relatively high wind loading due to its location at the confluence of two rivers. These elements meant that a completely different supporting system to that used at Marina Bay Sands was required for the skybridge.

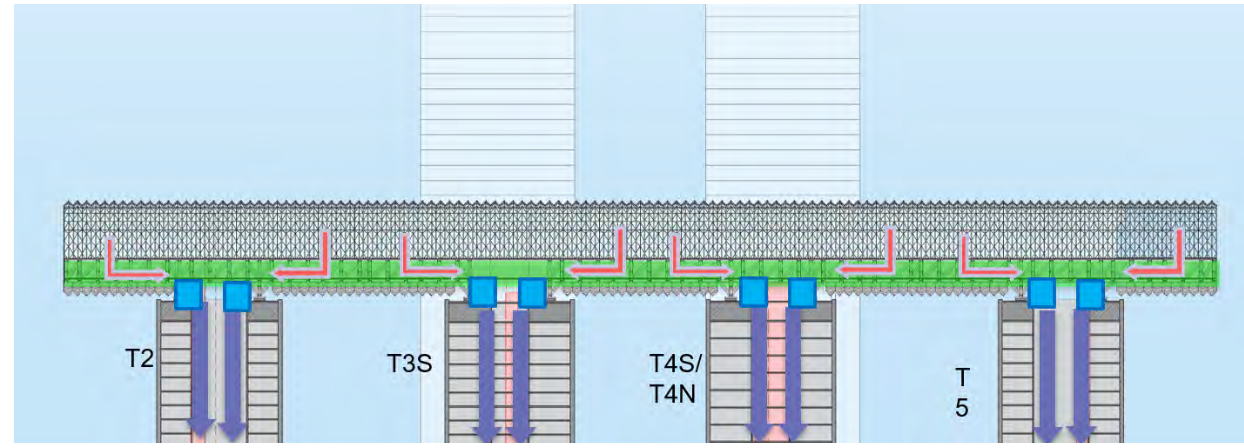
The Arup team compared different designs, with the skybridge fixed to or isolated from the towers, to determine the best option from a design and cost viewpoint. The stiffness of the building under wind loading required careful consideration, as movement in the towers needed to be kept at a minimum for the comfort of the occupants in the high-rise elements where the residential and hotel floors are located.

The baseline case saw The Crystal fixed rigidly to the top of all four towers, monolithically linking the buildings. However, this led to a design with excessive steel tonnage. The use of movement joints – as used in Marina Bay Sands – was ruled out because in extreme seismic events the towers could potentially move up to 3m apart. The team concentrated on exploring design options using bearings that would isolate the skybridge from the towers. LS-DYNA models of the four supporting towers and The Crystal were developed to analyse the dynamic interaction during seismic events. Analyses were carried out to extreme earthquake levels to justify the structural performance of the design. In total, 900 analyses were run over the course of the project; with 30 hours' run time typically required per model, approximately 27,000 hours of modelling were carried out.

These studies supported the hypothesis that the isolation options were the most beneficial solution, reducing the shear forces at the base of the towers by up to 30% compared with the fixed skybridge option.

A combination of seismic bearings – friction pendulum bearings (FPBs) – and dampers were used in the final design. The 2m-diameter bearings, 26 in total, have a level of friction that means they do not move below a certain force. Under normal load conditions and level 1 earthquakes, the FPBs are fixed and The Crystal does not move relative to the towers. Stresses arising from low seismic activity, wind and thermal movements are all resisted by the main structure.

However, under moderate or severe earthquake conditions (level 2 or 3), the bearings allow movement and the skybridge can move relative to the towers, thus dissipating the energy and helping to mitigate the effects of the earthquake. The dampers ensure that



12.

12. A connecting refuge area below The Crystal reduces congestion during evacuations

13: Friction pendulum bearings were used to support The Crystal and accommodate seismic loads

large forces, as well as the relative movement between the skybridge and supporting towers, will not be transferred into the skybridge structure. A 1:25 scale shaking table test was carried out to demonstrate the seismic performance of the six towers joined by The Crystal and the dynamically linked skybridges under extreme earthquake events.

The Crystal is made up of three primary steel trusses, interconnected by secondary steel and enclosed by a lightweight space truss enclosure. With different topping-out dates for each supporting tower, a detailed construction sequence analysis was carried out to prove the whole installation method was practical and safe. Arup worked closely with the contractor on the sequence analysis, installation method and temporary works design, before the sequence gained approval from the expert panel review.

Wind engineering

Due to the site topography, which includes rivers and mountains, extensive wind tunnel studies were carried out. The testing determined the wind load to be applied to the two 350m north towers and the torsional wind load for the six towers connected 250m above the ground by skybridges. The testing also took into account the interference effect of the many surrounding buildings.


13.

A wind climate analysis determined the correct design wind speed, with a 1:3,000 scale topography effect test determining the wind turbulence profile and scale. A multi high frequency force balance (HFFB) wind tunnel test determined the design wind loads of the six towers connected via skybridges. A high frequency pressure integration (HFPI) wind tunnel test in two independent laboratories calculated the structural wind loads for the conjoined six-tower structure. A separate HFPI wind tunnel test was carried out on the two 350m towers and the two 250m towers that are not below The Crystal. Finally, an LS-DYNA time-history analysis checked the performance of the isolation bearings between The Crystal and the top of the four supporting towers under the wind loads. Both the HFFB and HFPI tests were carried out on a 1:500 scale model. The detailed wind engineering testing and analyses determined that the structural design could be developed for lower wind loads than those in the design code, providing a cost saving.

Fire engineering firsts

The connectivity of the towers, both via The Crystal and at podium level, presented a number of complex fire engineering challenges. Arup introduced several fire engineering firsts for China on this project to resolve these issues. They included:

- emergency vehicle access provision for a podium roof, along with a discharge and evacuation procedure onto this roof;
- use of a refuge floor for evacuation transfer; and
- applying a performance-based design on such a large group of connected buildings.

Awards

2016
CITAB-CTBUH China Tall Building Awards
China Innovation Award
Honourable Distinction

2017
Hong Kong Construction Industry Council Innovation Award
Construction Productivity – Winner

2020
Council on Tall Buildings and Urban Habitat Structural Engineering and Fire and Risk Engineering
Awards of Excellence

Hong Kong Institution of Engineers Innovation Award
Grand Prize

Hong Kong Institution of Engineers Structural Division
Award of Excellence – China
Grand Award – Overseas Project

The Crystal has many different functions – it acts as the hotel lobby and a clubhouse for residents and has many public-access areas – so the design of its evacuation system was critical. With such high occupancy, the evacuation design includes 15 egress staircases that merge into ten staircases in the towers beneath. A connecting refuge area was designed below The Crystal to provide sufficient space for people to use each connecting staircase and to reduce congestion.

Evacuation lifts in the towers, which are also used for normal circulation, were included to improve evacuation efficiency and facilitate inclusive evacuation procedures. This allowed a reduction in the overall number of stair cores, increasing the useable floor area in the towers.

To assess the evacuation strategy, a benchmark was created by conducting a comparative evacuation analysis using a hypothetical design for separated towers with no skybridge. The design was based on a number of conservative assumptions, including a full maximum occupancy of people on all levels and a fire blocking the widest exit from the skybridge. The evacuation and fire modelling analysis demonstrated that, under each fire scenario, the building occupants would have sufficient time to evacuate before conditions became untenable, with an evacuation time shorter than that in the benchmark design.

15.

Arup's fire team modelled The Crystal using finite element analysis to optimise the fire protection of the structural steel under possible fire scenarios. The analysis identified that a majority of structural roof elements did not require additional fire protection, resulting in a significant cost saving. The smoke ventilation design took into account the impact of the wind due to the building's location and the height of the skybridge.

At the podium level, the fire and structural engineering teams worked together on a design that could structurally accommodate the large loads created by firefighting vehicles on the podium roof, liaising with the local fire department on the loading and to ensure there was sufficient space for the vehicles to safely manoeuvre on the roof. The fire engineering analysis for evacuation, fire and structural modelling was reviewed and approved by the fire engineering expert panel review.

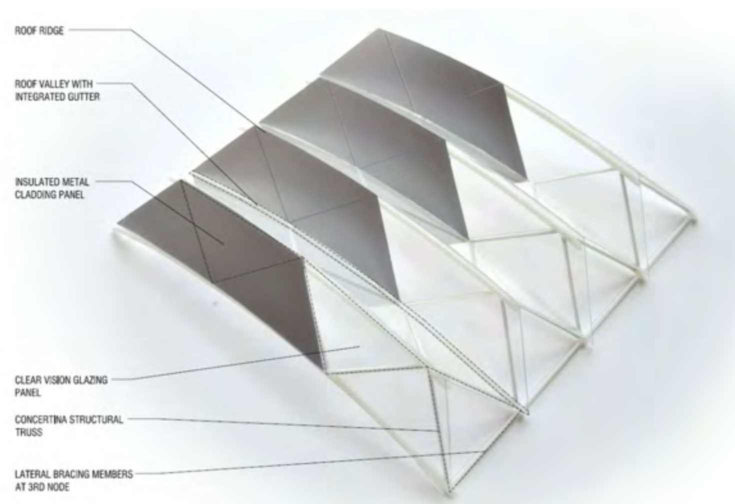
Sustainable building strategy

Holistic sustainability design strategies were adopted, with the aim of achieving a LEED Gold building certification. Arup developed solutions for façade optimisation and, working with the building services engineer, WSP, introduced energy-efficient building services systems, with indoor visual and thermal comfort modelling conducted to optimise envelope design and the heating, ventilation and air conditioning (HVAC) systems.

Energy-saving strategies include: low-emissivity glass to reduce heat gain; a high-efficiency energy centre; high-efficiency HVAC equipment; using natural ventilation where possible; water-side free cooling; air-side heat recovery; high-efficiency lighting fixtures; and daylighting sensors. These systems meant the project achieved a 16.5% energy cost saving in comparison with the American Society of Heating, Refrigerating and Air-Conditioning Engineers' baseline level. By using recycled air conditioning condensate and rainwater harvesting, 100% non-potable water sources were used for irrigation, with a 35% reduction of potable water use by occupants. There is 30% green coverage over the development.

The site's microclimate was studied to investigate the impact of wind and sunlight, with passive designs implemented where possible to mitigate the environmental impact on the building and its occupants. The Crystal's glazed envelope creates amazing views high above Chongqing; however, the quantity of glazing, the skybridge's south-facing aspect and the hot weather in the city during the summer presented design challenges. The Crystal's energy consumption could not be excessive, but occupants' thermal comfort had to be prioritised. Maintaining indoor thermal quality in an energy-efficient way was a complex task.

Arup carried out a building physics study to optimise the skybridge glazing. The design used an alternating glazing–cladding combination for a balanced outcome of skylight visibility and solar shading. After extensive study of different glare scenarios, fritted patterns of changing densities were introduced to the overhead glazing portion of the envelope to refine visual comfort – at the apex of the skybridge the maximum frit is 50%. The final design maximised views, ensured a comfortable environment and minimised energy consumption.



14.

14: An alternate glazing–cladding combination was used for The Crystal, to allow for both visibility and thermal comfort

15: The Crystal Exploration Deck provides a publicly accessible green space and views high above the city

Geotechnical challenges

The geotechnical design for the development was complex. The site slopes gently from south to north, and significantly to both the east and west, has varying ground conditions, and is constrained by existing buildings, roads and flood protection measures. It is located in a seismic zone and adjacent to the Jialing and Yangtze rivers, which have large seasonal fluctuations in water levels (the river water levels are also affected by the Three Gorges Dam, 600km away).

The site is made up of fill containing construction waste, silty clay, silt and cobbles, above shallow lying rock (mudstone and sandstone), with the rock head sloping across the site. The rock also has inclined fissures and interfaces that the design needed to take account of. Arup used a GIS model to balance out the cut and fill so that excavated soil from the site was used as backfill elsewhere to reduce cost.

The site's sloping nature presented potential stability problems, which needed to be addressed in the foundation design. A combination of foundation types were adopted, including shallow foundations, raft foundations, rotary-bored piles, percussion-bored piles, and hand-dug caissons of various shapes and sizes. The pile length varied from 7m to 44.5m.

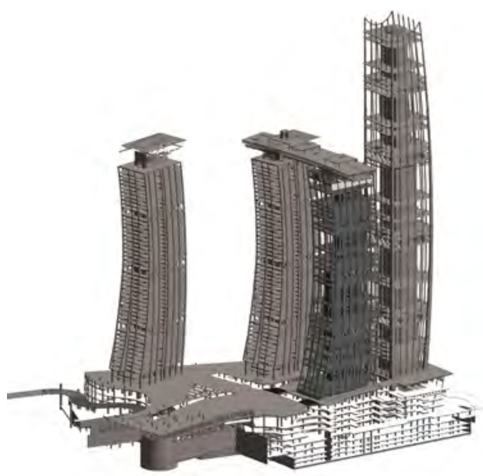
The foundations for the towers were formed from large hand-dug caissons (with pile diameters of up to 5.8m), with tension piles of various length used for anti-uplift. Where lower loads allowed, machinery-bored piles were used. Alternate foundations for the podium were constructed depending on whether the slab was founded on soil or rock. In the soil locations, hand-dug caissons were used under column locations for the compression loads, with tension piles for anti-uplift. Where the podium slab was founded on rock, footings were used under columns.

Although Chongqing is an area of lower seismic intensity than Beijing or Shanghai, because of the sloping site and adjacent rivers, various slope stability analyses had to be carried out to determine the horizontal load and design measures required to protect the structure from sliding. Plaxis and Oasys Slope software packages were used, incorporating gravity, groundwater, wind and seismic loads into the design.

Anti-slide stabilising piles of various diameters were used at 4m centres. To the west of the site these ranged from 1.6m to 3.1m in diameter; to the east of the site, 1.5m-diameter anti-slide piles were used in conjunction with the piles

16.

16: Due to the site's sloping nature, a variety of foundation types were used, including shallow foundations, raft foundations, rotary-bored piles, percussion-bored piles and hand-dug caissons



17.

for the tower foundations and podium. These provided resistance to horizontal forces and offered additional protection for the slopes from sliding. Similar to a number of elements of the design, the foundation systems were reviewed by both local and national expert panels, which took into consideration the site stability for both static and seismic scenarios and for the hand-dug caissons.

Delivering the design digitally

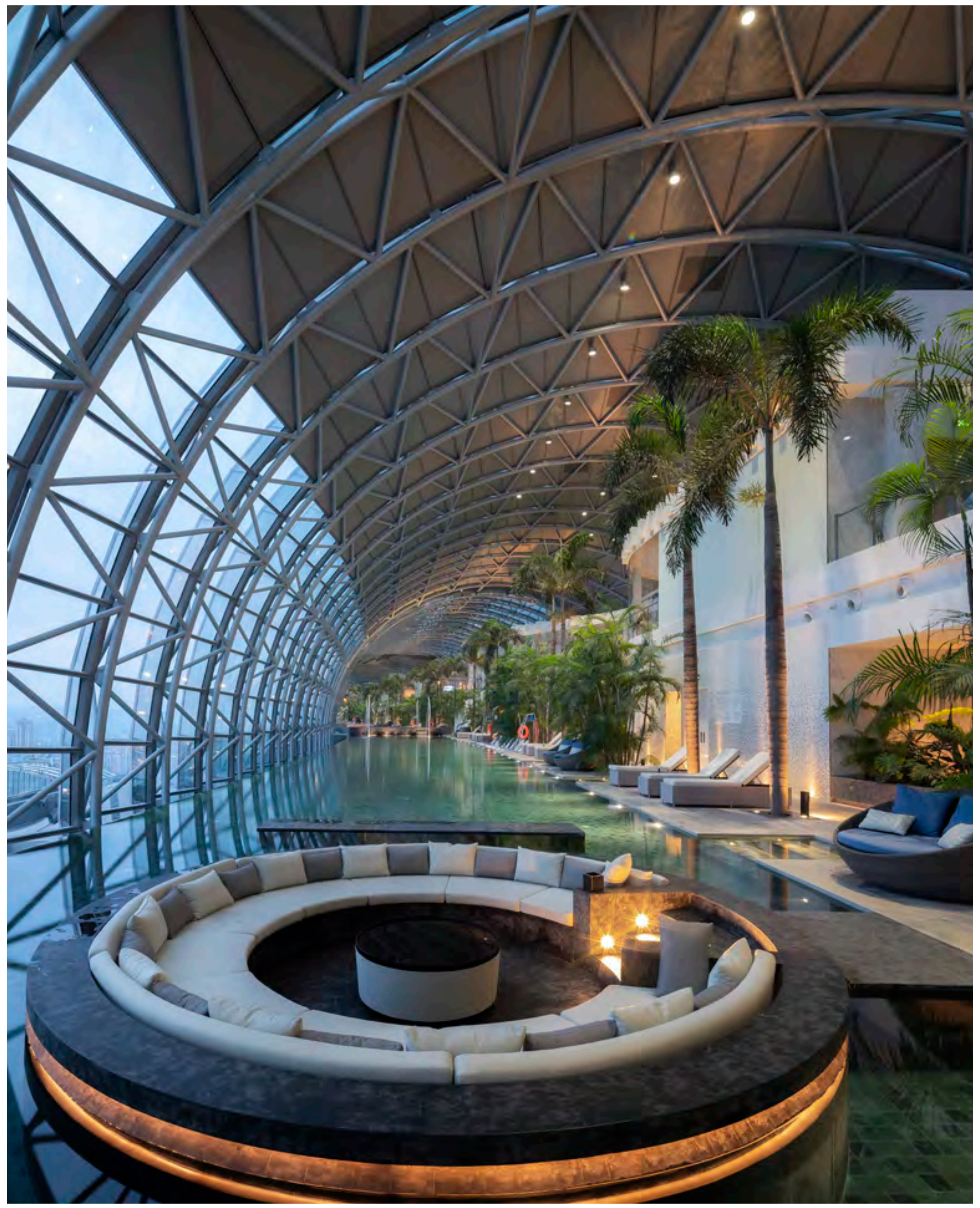
Considering the scale, complexity, and tight design and construction schedule for this project, advanced digital technology was used to deliver the design. Arup developed several automation tools to improve the design delivery and accuracy. In order to establish an efficient design and production process, Building Information Modelling (BIM) software was used including Rhino, Grasshopper, ETABS, Revit and Tekla, with tools developed to link the models and generate analysis results.

The tools improved the understanding of the project geometry; allowed greater efficiency of coordination between the design team; facilitated information transfer between the geometrical model, structural design model, production model and calculation reports; and gave the client a better understanding of the structural design through visualisation.

Arup used C# programming to develop custom Grasshopper components and generated multiple similar 3D tower models directly from the architect's 2D plans and elevations to carry out the sensitivity study of the building curvature and structural efficiency. During the concept and scheme design stage, the firm adopted parametric design tools to study the building geometry and column and core wall configuration, with Revit used during the design and construction stage for the drawing production and coordination.

Skyscraper city

With six of the towers linked in the air, Raffles City Chongqing is a mini skyscraper city. The design required innovative approaches across the full range of engineering disciplines to deliver this landmark development – one that serves as a symbol of the city's thriving past, present and future.



18.

17: Arup used a variety of BIM software, including Revit, during design and construction

18: The Crystal features many amenities, including a swimming pool

19: Raffles City Chongqing provides residential units, offices, serviced apartments, a hotel and many areas for the public to enjoy

19.

Authors

Penny Cheung was the Project Manager. He is a Director in the Shanghai office (and was formerly based in Chongqing).

Lu-Lu Du worked on the fire engineering design. She is an engineer in the Shanghai office.

Gary Ge led the geotechnical engineering design. He is an Associate in the Shenzhen office.

Antony Ho led the sustainability design. He is an Associate in the London office (and was formerly based in Hong Kong).

Michael Kwok was the Project Director. He is the Chair of Arup's East Asia Region Board and a member of the Arup Group Board. He is based in the Hong Kong office.

Allen Sun led the fire engineering design. He is Arup's East Asia region fire engineering skill leader and is an Associate Director in the Shanghai office.

Project credits

Client CapitaLand
Design architect Safdie Architects
Executive architects P&T Group
Design institute Chongqing Architectural Design Institute
Building services engineer WSP
Contractor China Construction Eighth Engineering Division and China Construction Third Engineering Bureau Company

Civil, geotechnical, fire, structural engineering and building sustainability services Arup: Andrew Allsop, Anthony Buckley-Thorp, Chao Cai, Fang Chen, Ivan Chan, Marco Chan, Chun-Lai Chen, Long Chen, Johnny Cheng, Eric Cheung, Penny Cheung, Ray Cheung, Robin Ching, Bao Chung Nguy, Matt Clark, Andrew Cowell, Gary Dodds, Karen Dong, Xiao Dong, Lu-Lu Du, David Farnsworth, Double Feng, Qian Gao, Gary Ge, Grace Gu, Shi-Yan Gu, Xiao-Juan Han, John Hand, Desmond Ho, Goman Ho, Yue-Qi Hou, Eric Huang, Ying Huang, Shao-Lei Jia, Yu-Huan Jia, Yu-Fan Jiang, Hong-Wei Jiao, Ling-Ling Jiao, Yong-Wook Jo, Darren Jones, Oi-Yung Kwan, Michael Kwok, William Lai, Francois Lancelot, Henry Law, Sam Law, Bill Lee, Winnie Lee, Sanya Levi, Er-Chun Li, Ji-Cai Li, Jiao Li, Jing-Yu Li, Teng-Fei Li, Xin Li, Zhi-Xiang Li, Zi-Xuan Li, Jie Liang, David Lin, Benjamin Liu, Cherry Liu, Jie Liu, Hai-Xia Lu, Ken Lu, Lu Lu, Zack Lu, Mingchun Luo, Yuvi Luo, Andrew Luong, Billy Ma, Yuan-Jun Mao, Brian Markham, Patrick McCafferty, Tim McCaul, Thi Minh Nga Vu, Phuong Nam Ta, Yen Ngan Nguyen, Minh Nhut Le, Kirk Nosho, Alvaro Quinonez, Dong-Wei Ren, Michelle Roelofs, Ngoc Ninh Pham, Michael Shearer, Pan Shen, Thomas Shouler, Bert Su, Allen Sun, Jessica Sun, Yi-Bin Sun, Shi-Xuan Tian, Alex To, Tri Nhan Tran, Huyen Trang Dinh, Tian-Yi Tu, Wang-Long Tu, Ethan Wang, Hong Wang, Hua wang, Michael Wang, Ming-Min Wang, Will Wang, Yuan Wang, Ke-Quan Wei, Jacob Wiest, Kin-Ping Wong, Chang-Song Wu, Shi-Chao Wu, Young Wu, Guang-Ting Xia, Fred Xiang, Irene Xu, Jing-Mei Xu, Derek Yang, Fang Yu Neptune Yu, Raymond Yu, Vala Yu, Wenting Yu, Mei-Ling Yuan, Xue-Wei Zeng, Ben Zhang, Brian Zhang, Bruce Zhang, Forrest Zhang, Kevin Zhang, Li Zhang, Oliver Zhang, Tom Zhang, Yan-Qi Zhang, Ye Zhang, Yue-Yue Zhang, Zi-Wei Zhang, Bruce Zhao, Gui-Lan Zhao Vivian Zhao, Li-Gang Zhu, Jin-Lin Zou, Lin-Juan Zou.

Image credits

1, 5, 15, 19: CapitaLand Ltd (China)
2: Google Earth Digital Globe
3, 14: Safdie Architects
4, 6–13, 16, 17: Arup
18: Arch Exist

Tunnelling for a cleaner city

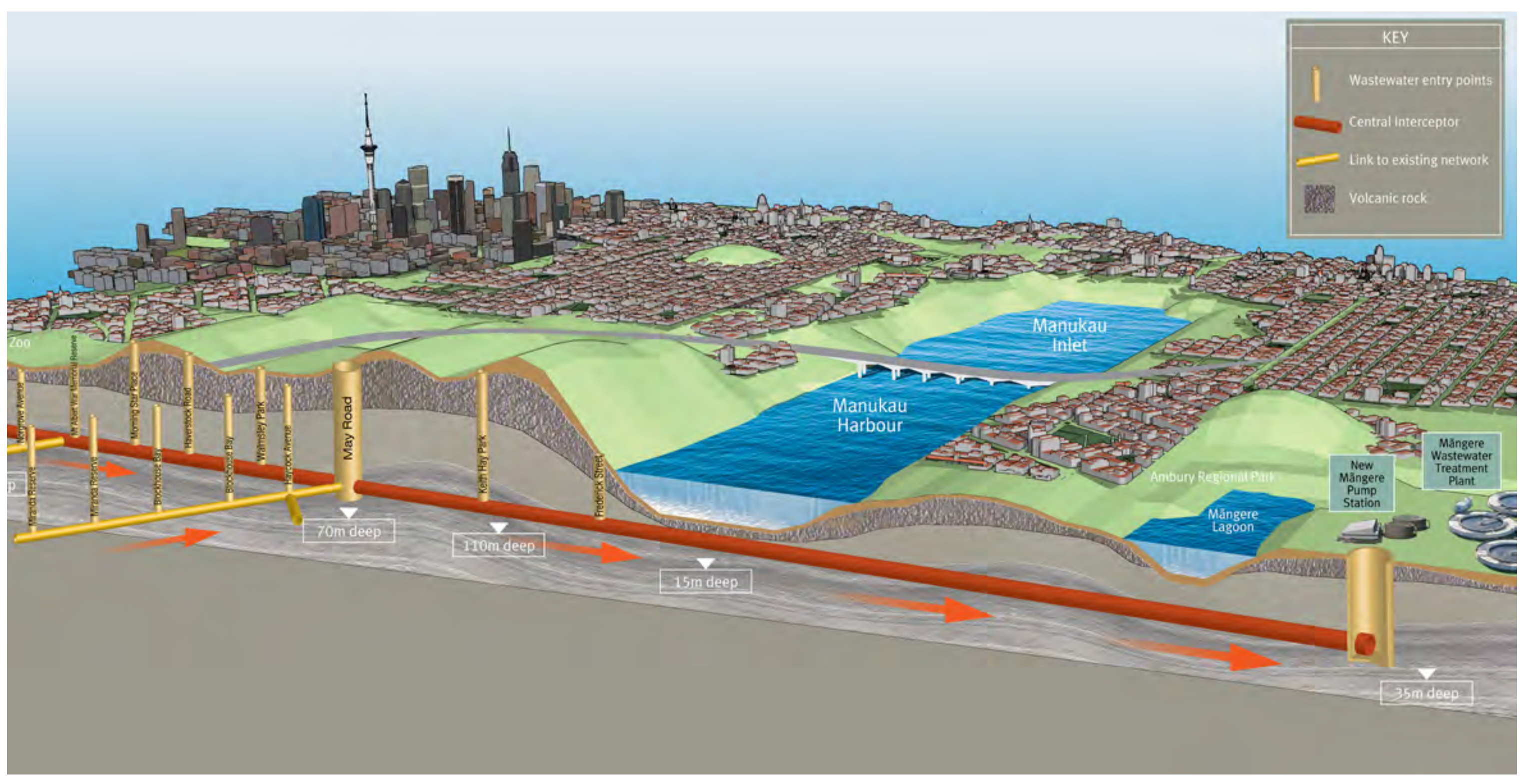
As Auckland continues to expand, its infrastructure has to grow with it

Authors Jochem Dorst and Andreas Raedle

1: When complete, the Central Interceptor will reduce wastewater overflows by 80%

2: The 14.7km-long tunnel will run from the suburb of Grey Lynn in Auckland to the Māngere Wastewater Treatment Plant

2.



1.

In recent years, Auckland has experienced significant overflows of wastewater from its sewage system. This pollutes the coast and beaches and endangers the health of anyone who takes a dip in the water. Without resolving this issue, the situation is only set to get worse: the city's population is projected to grow by 1 million over the next 30 years, putting further pressure on its ageing infrastructure, particularly the wastewater main that runs under the harbour.

To confront this growing problem, Watercare, the largest water and wastewater company in New Zealand, is constructing a new wastewater tunnel that aims to reduce overflows into inland waterways, improving water quality and social and environmental conditions. Ghella Abergeldie Joint Venture (GAJV) was appointed in early 2019 as the main contractor, with Arup commissioned by GAJV to provide detailed design services and construction phase support for the tunnel and shafts. When completed in 2025, the Central Interceptor will be the largest wastewater tunnel in New Zealand.

An ambitious plan

The 14.7km-long Central Interceptor tunnel will run from the suburb of Grey Lynn in Auckland to the Māngere Wastewater Treatment Plant in the south of the city via Manukau Harbour. With an internal diameter of 4.5m, it will run at a depth of 15m below the seabed – in some places as deep as 110m under the surface. The project also consists of 19 shafts, which will provide access and connect the existing pipe network with the new tunnel, as well as a pumping station, sewers, chambers and treatment facilities.

Arup's project scope includes design management, general geotechnical design, shaft temporary works and permanent lining design (structural and geotechnical), main tunnel lining design, link sewer jacking pipe selection and design, temporary works design for tunnelling operations for the main tunnel, digital engineering and construction phase support.

Arup has developed a range of innovative engineering solutions with the aim of improving productivity and safety while reducing risk. Many of these solutions are also geared around making the design and construction process more efficient through the use of digital modelling. There have been relatively few major tunnelling projects in New Zealand to date, so Arup's international experience of constructing wastewater tunnels has been invaluable.

Boring the tunnel

The sheer depth of the tunnel is a central challenge, requiring construction at 110m below ground level at some points. The tunnel will be excavated using a tunnel boring machine (TBM), which will work its way through a variety of soil conditions, ranging from unweathered to moderately weathered rock, and from weak to extremely weak soil. The TBM is scheduled to start digging in mid-2021, with its launch point at Māngere Wastewater Treatment Plant in south Auckland and its destination Grey Lynn in northern Auckland. Most of the passage is through East Coast Bays Formation rock, which comprises sandstone and mudstone. However, at the start, the machine will encounter Kaawa Formation (part of the Tauranga Group), a soft layer of sand, clay and silt that has lower strength and stiffness than East Coast Bays Formation rock. To help the machine navigate these variable conditions, different types of reinforcement are being used: softer ground will be steadied by a robust concrete liner with a mix of steel reinforcement bars and fibre, while for the more favourable conditions, steel fibre reinforced concrete will be adequate.

The pressure that will be applied by the TBM has been optimised for every part of the journey. As well as a variety of

3: The TBM will be launched from the Māngere Wastewater Treatment Plant site

4: Nineteen shafts will be constructed as part of the project to connect the new tunnel with the existing pipework and other facilities

3.

4.

5.

rock formations, it will cut through different depths of soil, with varying levels of pressure depending on what is above – for example, the 1.5km stretch across Manukau Harbour will place the lowest burden on the equipment. The tender specification demanded that the TBM operate in ‘closed mode’ under the harbour. This requires the excavation chamber to be fully filled and the face of the excavation to be pressurised to limit the amount of water seeping in and to minimise ground settlement on the surface and seabed.

Greater pressure generally causes cutter tools to wear out more quickly, meaning the boring team has to stop frequently for maintenance. Arup decided to simulate the actual tunnelling conditions the TBM would encounter to justify applying lower pressure where it was appropriate. Using Plaxis 3D software, the firm conducted a 3D finite element analysis that breaks down each tunnelling section into discrete parts, then models their performance and the required pressure based on the specific conditions. This meant the TBM could apply a significantly lower average pressure, thereby minimising wear and tear and allowing swifter progress.

The TBM will be launched in a novel way. Normally, TBMs operate by jacking against a static steel frame. For the Central Interceptor, Arup designed a ‘flying launch’ system: tension bars that push the machine forward with the help of a pressure ring. This means more efficient use of space at the bottom of the shaft, because the pressure ring and tension bars move forward along with the TBM. This method is also faster and wastes less material, as there is no need to erect and dismantle a temporary tunnel lining for the static frame.

The pipe jacking system

The two link sewers, with an overall length of 4.3km, which channel used water into the tunnel, will be constructed using the pipe jacking method, also referred to as microtunnelling, using micro TBMs. Australia and New Zealand standards for link sewers do not cover pipes constructed significantly deep below ground, as most sewers and cables are placed at a depth of less than 5m. Here, however, the depth ranges from 12m to 70m. Arup designed the pipe jacking in a similar way to a bored tunnel lining: rather than using a formula to come up with a conservative estimate for the load the pipes would have to bear, the effect of ground arching and soil lining was considered in the design, resulting in a design specifically suited to the local conditions.

Accounting for seismic activity

The tunnel lining design also needed to take into account New Zealand’s vulnerability to volcanic and seismic activity. The requisite standards make assumptions about the lining remaining fully bonded or slipping completely during an earthquake, whereas the reality is more likely to be somewhere between the two extremes. Arup went beyond these requisite standards, carrying out finite element analysis to characterise the potential friction where soil and lining meet and get a realistic idea of how seismic activity would affect the tunnel, rather than designing for the conservative worst-case scenario.

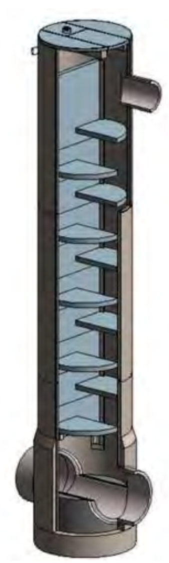
Designing the drop shafts

Sewage is siphoned into the tunnel via 19 drop shafts, which have an internal diameter of between 3m and 12m and reach depths ranging between 12m and 80m. Arup designed an innovative system of cascade shelves for these drop shafts, with the aim of improving the construction process. Central to this was building certain elements of the system in a factory, thereby enabling greater control over the quality and speed of construction and minimising the amount of time construction workers would need to spend in the deep shafts.

The elements constructed in situ include the lining and the corbels that carry the weight of the cascade shelving system, as well as the lower part of each shaft wall and the lowest shelf. The remainder is built as precast elements off site: integrated modules comprising the rest of the shaft wall and the shelves, which are lowered into each shaft.

Reducing corrosion risk

The team was asked to design the tunnel and shafts for a 100-year design life, with minimum maintenance required. This was complicated by the aggressive effects of the wastewater: biogenic sulphide causes corrosion and the rapid deterioration of ordinary Portland cement and steel reinforcement (which make up the tunnel’s concrete lining).



6.

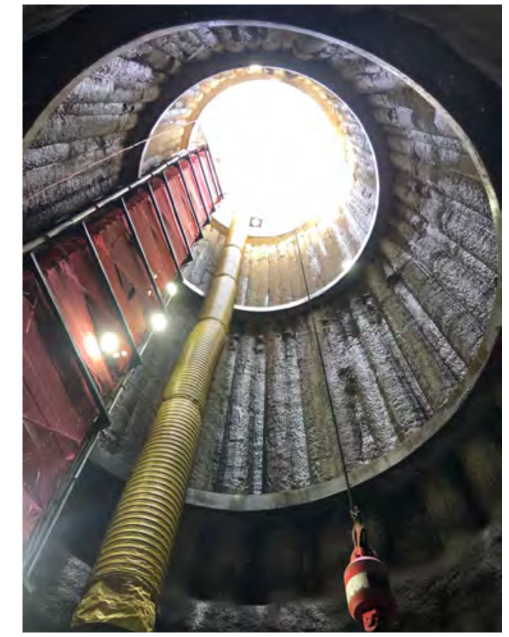
5: Two link sewers, with an overall length of 4.3km, will be constructed using microtunnelling

6: Arup developed an innovative precast concrete solution for the cascade shelves in the drop shafts

7.

7: The precast concrete tunnel linings elements were constructed off site

8: Bored pile walls temporarily support the large volumes of ground excavated during shaft construction



8.

Microbes found in sewers can also cause corrosion of the concrete lining, so a 3mm-thick layer of high-density polyethylene (HDPE), known to be resistant against microbial-induced corrosion, was applied to the inside of the tunnel. This was mechanically anchored to the concrete and the two elements were cast together off site. This single-step process allows greater control over quality and a quicker process than if the HDPE layer was constructed later on site.

The client had specified acid-resistant concrete (ARC) for a number of the drop shafts, but Arup worked with GAJV on an option to construct these using fibre-reinforced polymer (FRP). This system is more durable, easier to procure locally and quicker to work with. The firm carried out a feasibility study on the use of this material for the permanent wall lining, internal dividing walls and cascade shelves. One of Arup’s concepts, developed in collaboration with the University of Queensland and drawing on the shafts developed by the firm for the Silicon Valley Clean Water project, was a dual-skinned FRP outer and inner liner with reinforced concrete sandwiched between them. Ultimately, FRP was agreed upon for a number of shafts and Arup is undertaking a peer review of the shaft ideas to finalise the design.

Safe temporary works

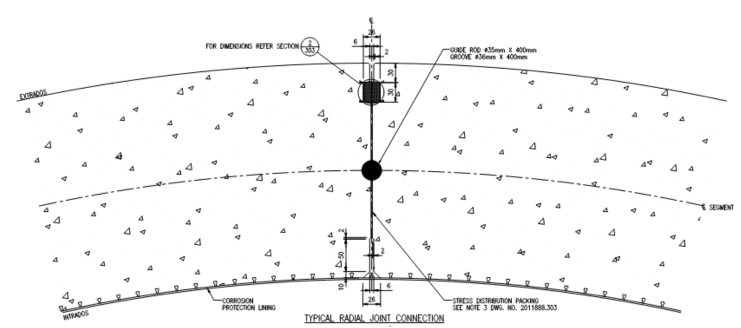
To ensure a safe working environment while the project was under construction, Arup’s geotechnical team worked with in-house rock mechanic experts to develop a temporary rock support system that took into consideration the depth of the works and the weak sedimentary rock around them. Arup challenged standard practice in New Zealand by using the real conditions of the rock – discovered through rock support interaction analysis and finite element modelling – rather than working from approximations. This took into account factors such as the natural relaxation of the rock and the fractured nature of the East Coast Bay Formation and resulted in a highly optimised design that will save cost and time. And, as less construction activity needs to take place underground, the health and safety aspects of the project have been improved. Arup also developed an effective inspection and quality control proposal to minimise human involvement in the construction of the wastewater environment.

The firm worked to improve the process of designing the bored pile walls, which are used to temporarily support the large volumes of ground excavated from the shafts. There is a margin of error as to where the piles are placed relative to the position set out in the design, which could mean a smaller contact area between intersecting piles and therefore a weaker structure. Calculating the worst-case scenario would normally be a labour-intensive process using CAD software and plenty of approximations – a method that can also lead to inaccurate results. Arup created a digital tool that used data about the position and potential variation of the piles to generate

9.

9: Mould of casting lining showing the high-density polyethylene used to protect the concrete against microbiologically induced corrosion

10: The corrosion protection lining was applied to the inside of the tunnel



10.

11.

a CAD-style image to illustrate the possibilities and the concrete strength required. These calculations are much more accurate than they would have been if calculated manually.

A system built to last

The Central Interceptor will have a 234,000m^3 capacity, enabling the storage, redirection and effective treatment of sewage for Auckland. This will have huge benefits for the health of the population and the environment, through cleaner waterways and beaches and the restoration of natural habitats. As Auckland continues to expand, its infrastructure has grown with it, ensuring a resilient environment that can meet the needs of future generations.

11: Once complete, the Central Interceptor will provide the essential water infrastructure Auckland needs as its population rapidly expands

Authors

Jochem Dorst is the Project Manager. He is an Associate in the Auckland office.

Andreas Raedle is the Project Director. He is a Principal in the San Francisco office (and was formerly based in Singapore and commuting on a regular basis to Auckland since 2017 for this project).

Project credits

Client Watercare
Contractor Ghella Abergeldie Joint Venture
Client's consultants Jacobs, Aecom and McMillen Jacobs Associates
Hydrogeology Beca
Civil and structural engineering, design management, general geotechnical design, shaft design, tunnelling design and construction phase design services Arup:
George Acuna, Mark Adams, Charles Allen, Renato Alcones, Mariela Angeles, Mia Balogh, Peter Burnton, Fergal Brennan, Fergus Cheng, Nurul Chowdhury, Patrick Collins, John Davies, Mahak Dewan, Andy Dodds, Jochem Dorst, Kaveesha Fernando, Megan Freeth, Mayurie Gunatilaka, Elizabeth Halsted, Ronald He, John Hildyard, Kavan Illangakoon, Charles Im, Sanket Jadhav, Dylan Jayamaha, Jasper Jiang, Karen Jodinata, Sharyon Jonkers, Shashank Kumar, Thida Kyaw, Daniel Lambert, Hannes Lagger, Ching Lau, Anna Liu, Mikel Llaneta, Harry Lovelock, Steve Lu, Xiangyue Luo, Rob MacCracken, Gaurav Mathur, Wesley Mauafu, Sue Myocevich, Jake Naran, Andy O'Sullivan, Christine Park, Tommy Parker, Sarah Peters, Don Phillips, Seth Pollak, Sue Poo, Andreas Raedle, Rajvinder Sethi, Matthew Simmons, Shane Small, Aoife Staunton, James Stringer, Leo Suhaendi, Podianko Surya, Dean Sykes, Sergei Terzaghi, Michael Tran, Nina Tropina, Yannis Vazaios, Francois Vermaak, Chris Vorster, Jack Wang, Citra Wicaksana, Hannah Willis, Ricardo Wong, Yi Yang Lee, David You.

Image credits

1, 2: Watercare
3, 4: Ghella Abergeldie Joint Venture
5–10: Arup
11: Milosz Maslanka/Shutterstock

1.

Going green

This urban development prioritises sustainability and wellbeing, enhancing the city environment

Authors Kennis Chan, Tony Lam, Zoe Lee, Ka-Man Miu and Tony Tang

1: K11 ATELIER King's Road has been awarded a Platinum Final Certification rating for both LEED and WELL

When envisioning K11 ATELIER on Hong Kong's King's Road, property development company New World Development wanted to create a Vertical Creative City – an office and business complex containing a host of lifestyle amenities, in which entrepreneurs and thinkers would come together to exchange ideas and drive the city's growth. Arup previously worked with New World Development on its K11 ATELIER Victoria Dockside development on the Hong Kong waterfront of Tsim Sha Tsui. The firm was commissioned on the K11 ATELIER King's Road project to provide sustainability, mechanical, electrical, plumbing and façade engineering services.

This new building is an example of both an inspiring and sustainable workplace and a piece of city-centre architecture that benefits the surrounding community – bringing greenery and liveliness to the neighbourhood and fostering a creative and productive working culture within its walls. In creating the building, sustainability and wellness guided every aspect of the decision-making process. More than 70 eco-friendly design features – reflecting six of the 17 UN Sustainable Development Goals – ensure the building achieves the highest standards of efficiency. Together, these have brought the project a host of accolades and set it up as a standard-bearer of green construction in Hong Kong and a model for office developments in the 21st century.

A revitalised site

K11 ATELIER King's Road is a 45,290m², 125m-tall office development in North Point on Hong Kong Island. The site was transformed into its current form over a period of four years, from the time the land was secured to when the first tenants moved in. The 22-storey structure includes office space, exhibition and event areas, retail outlets, restaurants, bars, a sky garden and dozens of other amenities aimed at enhancing the lives of the people who inhabit the building. The design itself was developed with occupiers' wellbeing in mind, and the development has also enhanced the local cityscape through its design and its green façade.

Arup worked alongside a range of consultants and subcontractors on the project, using a communication platform called the Internet Project Communication Centre to improve productivity and help reduce the amount of paperwork used in project administration. Building Information Modelling (BIM) was also used throughout to strengthen coordination, minimise wastage and streamline the project process.

Arup's work on K11 ATELIER King's Road was focused around three central missions: to create a sustainable working environment; to improve the site context, streetscape and neighbourhood; and to promote green design in the city.

Green design

K11 ATELIER King's Road achieves a Platinum rating under the US Green

3.

Building Council's LEED system. It was also the first project in the world to achieve all measures under the WELL Building Standard Pre-certification scheme, which identifies buildings and interiors that have outstanding health and wellness performance. Upon construction completion, the project was the first building in Hong Kong to achieve both LEED and WELL final Platinum certifications. The design received support from the Hong Kong authorities from the beginning – it was the first project to receive a loan under the territory's new green financing initiative.

Arup led the sustainability strategy for the building and achieved these goals using a diverse range of measures at every step of the development, starting with the construction process. Wherever possible, Arup specified regionally sourced materials with recycled content and wood that had achieved Forest Stewardship Council certification. Glass panels were commissioned in a uniform, customised size to ease the production and delivery process.

As an example of the way sustainability was built into all aspects of the design, a curtain wall system with insulated glass units and low-emissivity coating was selected for the office areas owing to its heightened energy performance – as well as because of its acoustic control abilities, given the noisy urban context. Arup conducted various analyses to determine the window to wall ratio and type of

2.

2: Over 230,000 plants are featured around the structure

3: Sustainable materials were sourced where possible, including wood with Forest Stewardship Council certification

glass, including building energy modelling, dynamic thermal modelling and daylight simulation. Special design workshops were held to review and refine the plans for maintaining the curtain walling in the most efficient way.

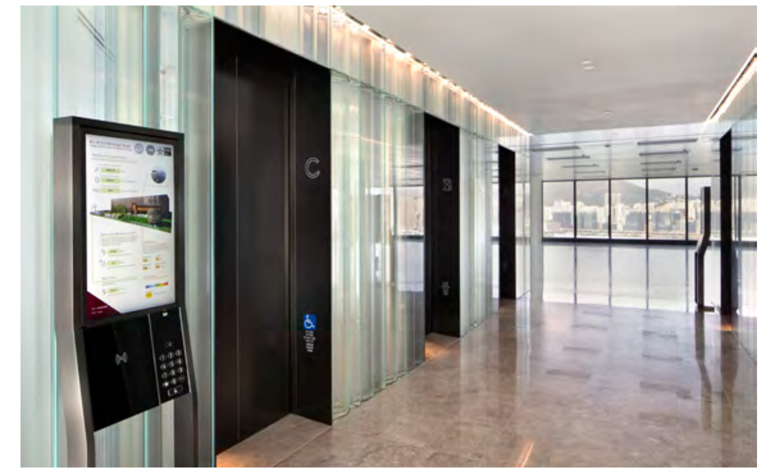
The most eye-catching element of the sustainability plan is the abundance of greenery. More than 230,000 plants are embedded across the building, including 40 different flowering, fragrant and edible species. The plants are scattered across the building's envelope, including the sky garden and the façade around the podium. This is far above the statutory requirements, which specify that greenery needs to equate to only 20% of the site area of a structure. In total, the greenery contributes to the carbon sequestration of 4 tonnes of CO_2 each year and reduces the urban heat island effect in this high-density neighbourhood. It has also promoted local biodiversity, with birds and butterflies drawn to the structure.

Reusing resources

Much of the sustainability strategy is based around the generation of renewable energy. The measures geared towards energy efficiency led to a saving of more than 30% compared with the local building energy code. Central to this is the 220m² hybrid solar photovoltaic and thermal (PVT) installation on the roof – the largest of its kind for a commercial development in the Australasia region and the first example of a commercial building in Hong Kong adopting this technology. Comprising a total of 138 panels, the system generates electricity for lighting the building's lift lobby and hot water for its showers. The panels have a higher energy efficiency than conventional photovoltaic systems; this was required because of the limited amount of surface area available on the tower.

The PVT installation is complemented by a 3kW wind turbine which powers the building's external lighting. The lighting system requires minimal maintenance and has motion sensors for energy saving. Together, the PVT and wind turbine generate about 77,000kWh of renewable

4.



5.

4: The hybrid solar photovoltaic and thermal installation on the roof generates electricity for lighting in the lift lobby and hot water for the showers

5: Monitoring devices in the lobby track and display changes in temperature and humidity

energy per year, which accounts for 1.3% of the building's total energy use. By participating in the Hongkong Electric Company's feed-in tariff scheme, it is also supporting the adoption of renewable energy on a wider scale.

Arup's design of the building services contributes an additional 30% saving in energy use, compared with the standard set by the American Society of Heating, Refrigerating and Air-Conditioning Engineers.

Effective waste management was also a priority. Recycling facilities have been provided on each floor, with a dedicated recycling storage area located on one of the lower floors so that the cleaning company has easy access. The volume of food waste is estimated to have been reduced by 85% via a system that converts it into environmentally friendly fertiliser, about 15kg of which is generated each day for use on site.

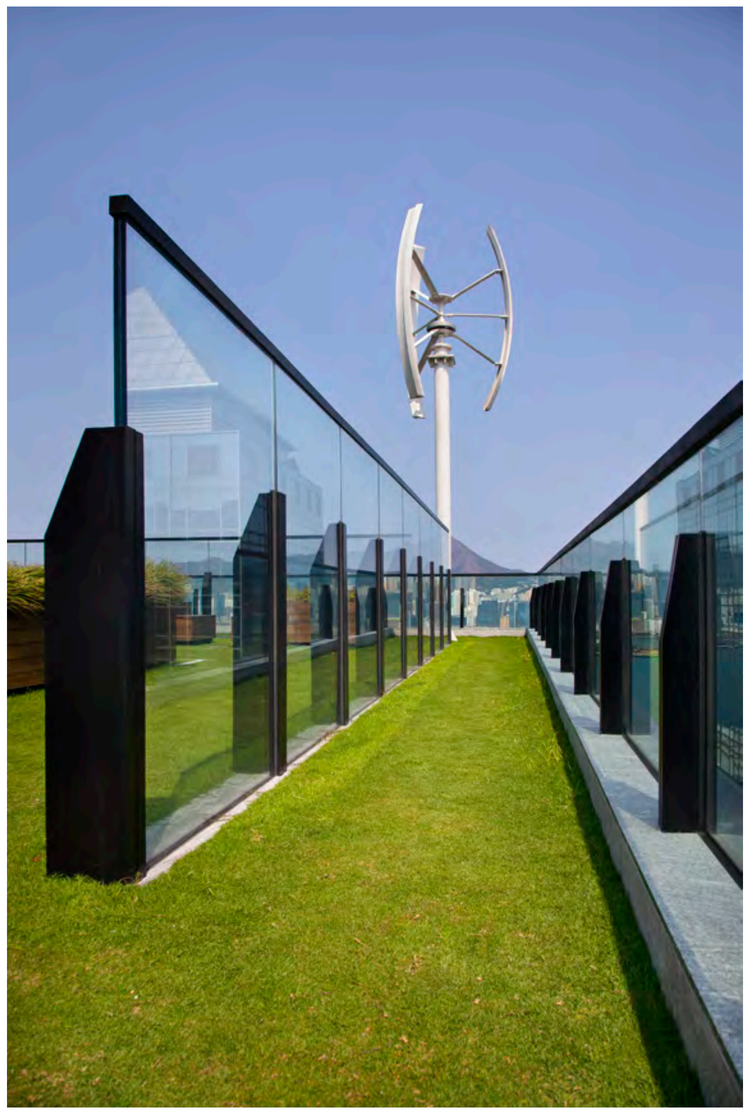
Water conservation has been tackled through various methods. The bleed-off from the cooling tower is used to flush toilets, and a rainwater harvesting system reduces freshwater consumption by an estimated 65%. A differential-pressure pumping system allows water pressure to be automatically adjusted depending on demand on taps at different times.

The drive for sustainability also encompasses efforts to promote environmental awareness. To that end, monitoring devices tracking and displaying real-time changes in temperature and humidity have been installed in the main lobby. Meanwhile, electric vehicle chargers have been provided in the car parking area to encourage air-pollution-free motoring.

Wellness

Arup's approach to wellness on this project was an extension of its environmental sustainability proposals.


6.


7.

6: The LED lighting system saves energy by being linked to daylight sensors and is equipped with glare-free luminaires

7: The roof garden microclimate is kept at a comfortable temperature year-round through the placement of 2m-high shields that protect the area from winter winds

With any given measure, both the environment and the people using and living around the structure were taken into account.

The building interior was designed with these principles in mind. The LED lighting system is linked to daylight sensors for energy saving and equipped with glare-free luminaires, while the high-performance, low-energy glazing provides solar control as well as excellent daylight. The air-handling units and supply diffusers ensure that the air is of the highest quality, with air movement and thermal comfort closely monitored and optimised. They also filter out pollutants such as PM2.5, PM10 and volatile organic compounds (VOC), and use ultra-violet germicidal irradiation to eliminate bacteria and mould. Lead-restricted building materials and those with low levels of VOC have been used for the safety of building occupants, and sound and smell have been considered throughout to create a soothing experience within the structure.

Similarly, the rooftop garden is a green feature but also gives those working in the building a pleasant environment in which to spend time and interact with each other, encouraging creative collaboration and fostering a sense of community. The garden's microclimate has a comfortable temperature, which is controlled by strategically placed 2m-high shields that protect the space and its benches from winter winds. These measures, designed using computational fluid dynamics analysis, have made the outdoor space usable all year around – it would otherwise have only been tolerable for 54% of the winter. On the rooftop, a weather station monitors the outdoor climatic and environmental conditions, including temperature, solar radiation intensity, wind speed and more. This information is collected and translated into a thermal comfort index for display on a sustainability dashboard at the threshold of the sky garden. When stepping out, users can glance at the display to get the latest updates and recommendations, as well as a rundown of the building's renewable energy generation.

Awards

2020
MIPIM Asia Awards
Best Green Development – Winner
Best Office Development – Winner

Council on Tall Buildings and Urban Habitat
Structural Engineering
Best Tall Building 100–199 meters
Award of Excellence

Urban Land Institute Asia Pacific Awards for Excellence
Winner

The roof also houses a 70m² span of urban-farming planters, which means people can take up gardening and enjoy the freshly grown vegetables and fruits at K11 ATELIER's healthy-eating-focused restaurants and cafés. A 170m-long jogging path made of real grass runs alongside the planters, encouraging exercise and an active lifestyle. Each floor of the building includes a nursing room for new mothers. Several have direct access to balconies, so users can step outdoors into the fresh air.

The building also houses a public art gallery, which helps to further promote mental wellbeing. Crafted design elements add a human touch: granite stones excavated on site during construction have been upcycled as a stone feature wall. In addition, the K11 ATELIER ACADEMY in-house curation team puts together an eclectic mix of wellness, education and interaction programmes for the workforce.

Site planning

As well as considering the needs of the building's users, Arup also took into account how the development might affect the people living and working around the building. K11 ATELIER King's Road is located in a dense part of a dense city, and is a towering, visible presence. However, its form and envelope were designed to reduce the negative impact of this presence; rather than being constructed simply of glass and steel, the aim was to create a green, pleasant view.

Usually, the bases of office buildings in Hong Kong are fully enclosed, creating large, obtrusive bulks at ground level that block natural ventilation and the visual connection and access between streets. With K11 ATELIER King's Road, a glazed, transparent entrance lobby is set back from the street on three sides to create a landscaped open space near the building, creating better walkability and ventilation. The setbacks range from 1.4m at the back to 12.8m on the main King's Road, the latter of which creates a distance of 42.8m from the building opposite. This configuration means that on the ground floor only 52% of the site comprises built area, compared with 100% on most similar properties. Furnished with greenery, these voids occupy valuable rentable space, but the design team decided to prioritise the enrichment of the street experience for pedestrians over financial returns.

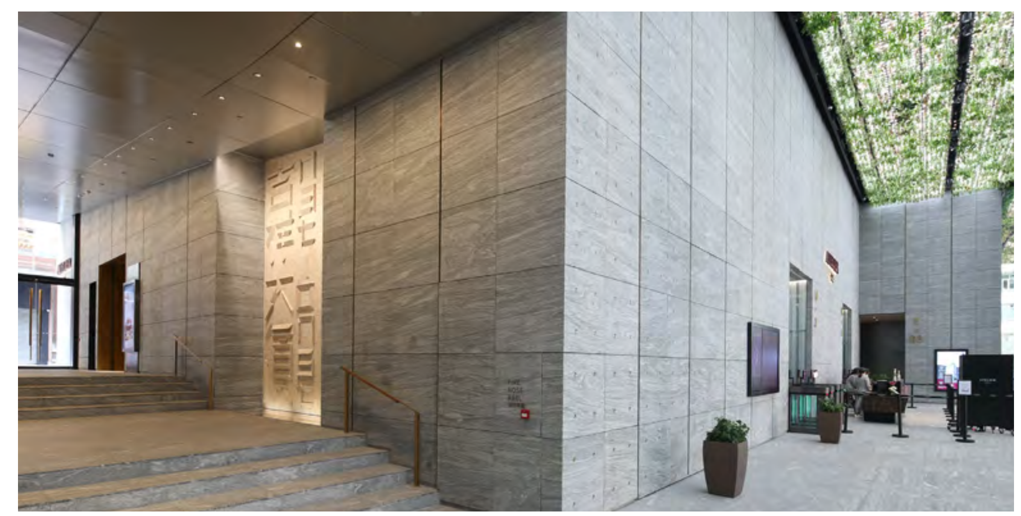
Additional greenery, designed by P&T Group, interior designer ESKYIU and landscape designer P Landscape, comes in the form of a floating 'green box' that hovers 9.2m above ground level at the base of the office tower's raised podium. This gives shelter to the people passing through the open space below and adds visual appeal to the structure.

The ground floor restaurants are open to the public. The exhibition spaces on the second floor are designed to be multifunctional, and are equipped with measures to support rapid reshaping, such as a computerised lighting control system, movable partitions, curtains, and a ceiling and column hanging system, all of which

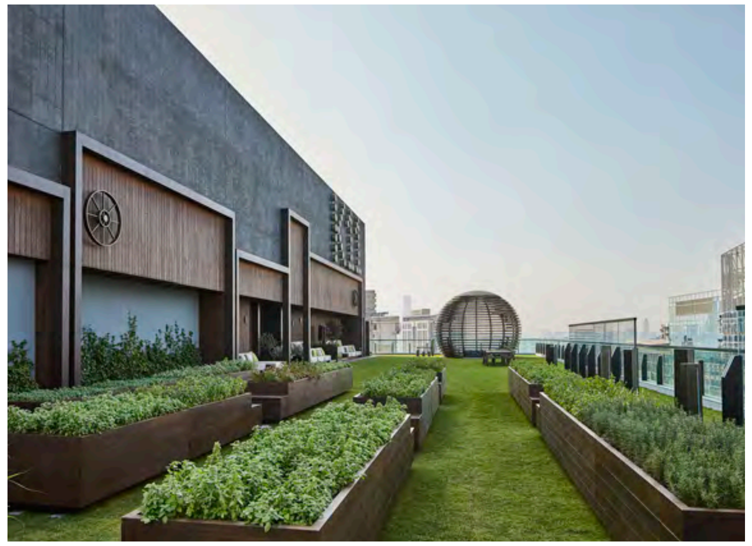
8: A floating 'green box' at the base of the tower's raised podium gives shelter and enriches the environment for pedestrians

9: Granite stones that were excavated from the site during construction were used in the lobby walls


8.


9.


10.


11.

mean the space can easily be transformed for different public events.

Building envelope

The building's envelope was designed with aesthetics in mind – creating appealing views from both inside and out. The higher floors that overlook the sea have a rectangular layout, to maximise the vista, but on the lower levels, which look over industrial buildings, the façade has been designed with irregular shapes and protrusions on which to place greenery, offering passers-by and inhabitants the experience of lush foliage amid this concrete-heavy neighbourhood, as well as relief from the sun. A geometric glaze reflective analysis was conducted to ensure the surface of the building is glaze-free, for the benefit of surrounding buildings.

Hong Kong is prone to typhoons, which means that planting outdoors at this scale was not straightforward, particularly because of the building's height and the risk of greenery falling down. Arup conducted computational fluid dynamics analysis to determine the wind pressure at all points of the building under typical Hong Kong typhoon conditions. The firm used these to create offsite mock-ups, placing the vertical greenery to account for the findings and demonstrating the design's safety to local authorities. Maintenance of vertical greenery is also a challenge; behind the green surface there are accessible corridors so that the plants can be easily cared for.

A prestigious location

The aim at K11 ATELIER King's Road was to go above and beyond statutory requirements and general practice when it came to sustainability and wellness. Since becoming fully functional towards the end of 2019, K11 ATELIER King's Road has already become one of the city's most prestigious commercial addresses: the anchor tenant is a Fortune 500 multinational corporation, which sits alongside a host of other top local brands and global companies.

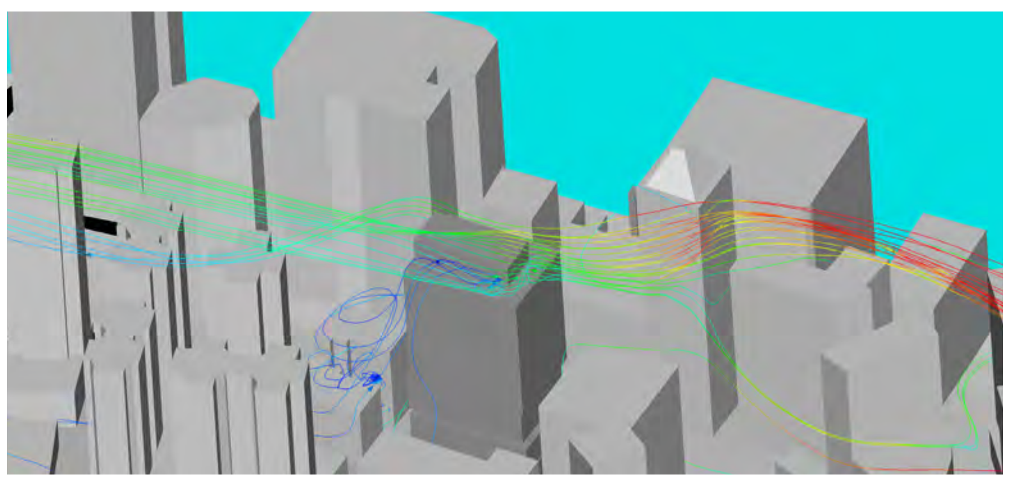
This Vertical Creative City is already giving a boost to this old commercial district and bringing business opportunities to the locality. But perhaps more than that, it has contributed substantially to the creation of a greener, healthier neighbourhood and provided an example for future office developments to follow.

10: The building's façade has been designed to have irregularities on which to place greenery

11: The roof garden provides a peaceful oasis in the busy city

12. Arup carried out a computational fluid dynamics analysis to determine wind pressure across the building in a typical Hong Kong typhoon scenario

13: K11 ATELIER King's Road opened at the end of 2019 and is a shining example of a sustainable, wellness-focused building


12.

13.

Authors

Kennis Chan is an assistant engineer and sustainable system specialist in the Hong Kong office.

Tony Lam was the Project Manager and is Arup's East Asia region building performance and systems skill leader. He is an Associate Director in the Hong Kong office.

Zoe Lee is an assistant engineer and healthy building specialist in the Hong Kong office.

Ka-Man Miu is an engineer and renewable energy specialist in the Hong Kong office.

Tony Tang is an engineer and green building specialist in the Hong Kong office.

Project credits

Client New World Development Company Ltd
Architect P&T Group
Structural engineer CM Wong & Associates Ltd
Management contractor New World Construction Co Ltd
Landscape designer P Landscape Co., Ltd (Thailand)
Interior design (tower and podium) ESKYIU
Building services and façade engineering, sustainable building design and sustainability consulting Arup:
Gigi Kam, Gary Chan, Kennis Chan, Nathan Chan, Josh Cheng, Vincent Cheng, Emily Koo, Tony Lam, Zoe Lee, Kenneth Leung, Ricky Li, Ka-Man Miu, Katsuya Obara, Tony Tang, Jenny Zhao.

Image credits

1, 13: Marcel Lam Photography
2, 4–7, 9, 10, 12: Arup
3, 8, 11: New World Development Company Ltd

Panning for scientific gold

Carving out a world-class scientific research facility a mile below ground

Authors Gordon Carrie, Seth Pollak, Richard Potter and Josh Yacknowitz

After operating for 125 years, in which time it yielded over $1bn worth of gold, in 2002 mining operations ceased at the Homestake Gold Mine in Lead, South Dakota. Since 2006, the mine has been repurposed in the search for a different kind of treasure: that relating to subatomic phenomena. Arup is enabling Fermilab, America's particle physics and accelerator laboratory, to expand the existing Sanford Underground Research Facility (SURF) which is in the decommissioned mine. Located nearly a mile below ground, the Long-Baseline Neutrino Facility (LBNF) will house an experiment that aims to improve our understanding of neutrinos and their role in the universe.

Funded in part by the United States Department of Energy and the European Organization for Nuclear Research (CERN), the new facility will be home to the Deep Underground Neutrino Experiment (DUNE), which will include the world's largest neutrino detector. DUNE's origins are in the 1960s, in the same Homestake mine. A solar neutrino detector installed then by chemist Ray Davis from Brookhaven National Laboratory at the mine's 4850 Level (4,850ft/1,482m below ground) helped lead to discoveries about the nature of neutrinos; work that earned a Nobel Prize and that will continue at the LBNF. DUNE is a collaboration between over 1,000 scientists, 180 academic institutions and research organisations from around the world.

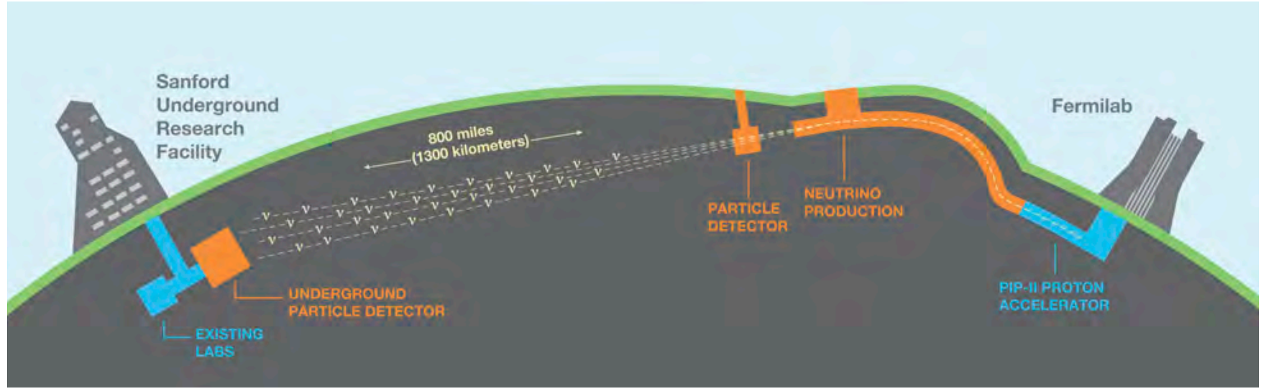
Building on its experience from working on deep underground tunnelling for rail projects, as well as other science and energy facilities, Arup is helping to develop all aspects of the facility – both the underground elements and site infrastructure on the surface. The firm is tackling unprecedented engineering challenges to help create the massive underground caverns that will house the detector; designing the cooling and ventilation systems in the new caverns for LBNF; and providing power, communications and life safety systems

1.

2.

1: The new Long-Baseline Neutrino Facility will expand the existing Sanford Underground Research Facility, located at the former site of the Homestake Gold Mine

2: The LBNF will house the Deep Underground Neutrino Experiment detectors, located almost a mile underground, which will be used to conduct experiments into the nature of neutrinos



3.

3: Neutrinos will be beamed 1,300km through the earth from the LBNF Near Site in Illinois

4: Some 725,000 tonnes of rock will be excavated and deposited into the existing Homestake Open Cut

5: The neutrino detector is made up of four cryostats

for the scientists who will be working a mile below ground. LBNF is located at the 4850 Level, SURF's main science area, and is accessible from the surface through the laboratory's two main shafts (the Ross and Yates shafts).

Arup is providing tunnelling, mechanical/electrical, plumbing, fire protection, communications and fire/life safety engineering; cost/schedule consulting; structural engineering services; civil, architectural and mine consulting; and other specialist services via sub-consultants for this 17,000m^2 (4.2 acre) underground facility.

Arup has worked on the design development of LBNF at SURF since 2013 and has been involved at the site for over a decade. In 2017, the firm finished the design of the enabling works package for the pilot tunnel construction, blast door installation, expanded surface site infrastructure and refurbishment of the former waste rock conveyance system – work that is near completion on site.

Arup delivered the final design for the facility in mid-2019 and major excavation will begin in mid-2021 to create the caverns that will house the experiment. Over the next three years, 725,000 tonnes (800,000 tons) of rock will be excavated and removed using the laboratory's upgraded rock handling system.

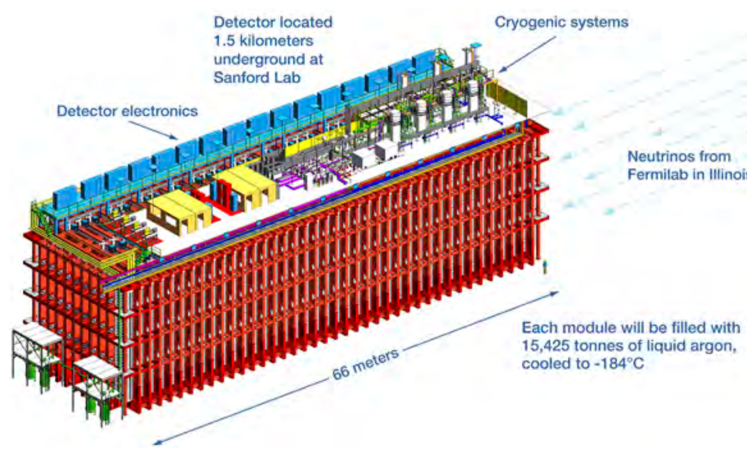
The origins of the universe

DUNE aims to answer questions about the nature of matter and the origins of the universe. It will be looking into topics relating to Einstein's Grand Unified Theory of forces, the birth of neutron stars and black holes, and why the universe is made of matter rather than antimatter. To help unlock these mysteries, scientists are studying the behaviour of neutrinos. The experiments have to take place deep enough below ground that interference from cosmic radiation is minimised. The LBNF Near Site, located at Fermilab's campus in Illinois, will generate neutrinos from its megawatt-class proton accelerator and beam them through the earth (without the need for a tunnel) to the LBNF Far Site Facility, located at SURF. The neutrinos will take just 0.004 seconds to travel the 1,300km (800 miles) to the LBNF, where they will be intercepted by the neutrino detector, which is made up of four cryostats – 66m-long, 14m-high sealed steel tanks that hold liquid argon – enabling scientists to observe their behaviour. Each of the cryostats will contain 15,425 tonnes (17,000 tons) of liquid argon (equivalent to the volume of eight Olympic swimming pools)..

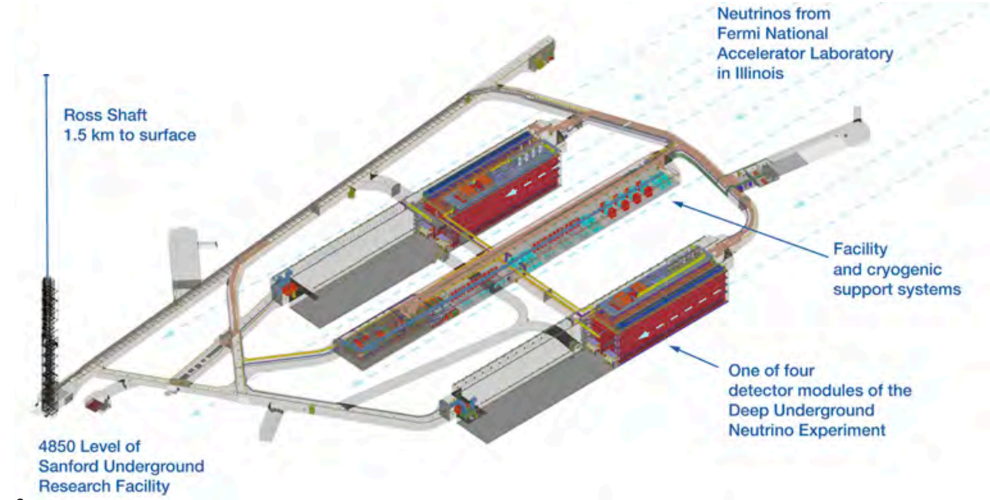
Geotechnical investigation

A comprehensive geotechnical investigation – involving the use of historical observations and existing Homestake records, as well as site investigations and laser scans that collated as-constructed geometric information – formed the basis for Arup's excavation design. Four long horizontal borings were made through the future cavern site from existing tunnels on the 4850 Level. A robust laboratory testing programme helped define the strength and stiffness parameters of the rock.


4.



5.



6.

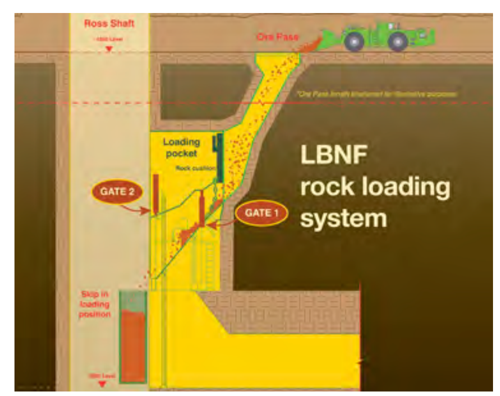

7.

The rock properties were further validated by an observational and back-analysis exercise that saw the design set of inputs (rock mass strength, in-situ stress and so on) applied to known cases in the mine of both successful excavations (such as the hoist room at the laboratory's 4550 Level) and 'failed' conditions (such as fractured, hour-glass-shaped rock pillars or slabbing tunnel walls). The in-situ observations were compared against the modelling results, with minor calibration adjustments made prior to undertaking the final design.

The rock conditions are well characterised from over a century of mining, as well as more recent underground civil construction works for SURF. The cavern locations are bounded laterally on three sides by existing tunnels (drifts) and vertically above and below by adjacent mine levels. The ready access to these areas, along with the information gleaned from the new horizontal boreholes and existing historical records, meant that Arup had far more detailed data than that typically available for a civil-type underground project. This enabled a well-defined 3D rock mass model to be developed and used in the design, ensuring the caverns could be situated and orientated outside of the influence of any rhyolite zones (brittle, glass-like intrusions that have the potential to shatter upon exposure) and persistent mineral infilled joint veins (historically a source of water transmission). As the joint veins generally run north–south, their influence is minimised by the orientation of the caverns, which are east–west to match the beamline direction.

Excavating the caverns

The facility will be housed in some of the largest caverns ever to be constructed at depth. The neutrino detector will be placed in two 150m x 20m x 30m-high chambers situated to either side of a central utility cavern (190m x 20m x 11m high), with a number of ancillary connecting tunnels and chambers to be excavated to support operations. The chambers will be formed using a drill and blast method, with explosives placed in drilled holes in the rock in a predefined pattern. All the loose blasted rock will be removed from the cavern via loaders and taken up the Ross Shaft in rock skips. At the surface, the rock will be crushed and transported 1,280m (4,200ft) using the newly installed overland conveyor system, before being deposited into the Homestake Open Cut. The Arup team strengthened the steel headframe at the top of the Ross Shaft, and designed utilities within the upgraded shaft. A new cage for personnel and equipment, as well as new rock skips for transporting the excavated rock, were designed and constructed by others.



8.

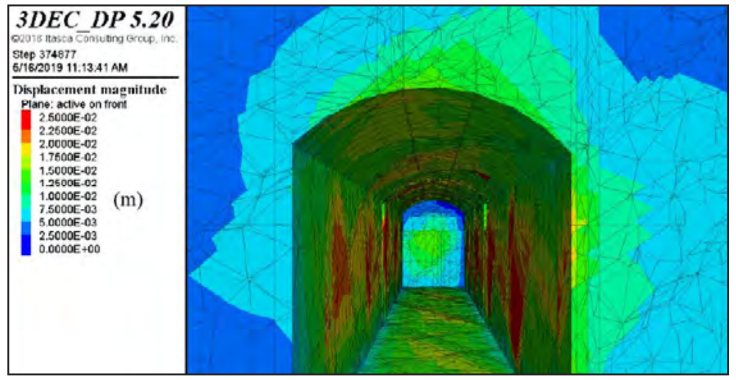
6: The four modules of the neutrino detector will be placed in two chambers situated either side of the central utility cavern

7: The Arup team strengthened the steel headframe at the top of the Ross Shaft and designed utilities within the upgraded shaft

8: Rock skips will take the loose blasted rock up the Ross Shaft to the surface

Building for science

Arup previously worked with Fermilab on the Illinois Accelerator Research Center located at their campus in Batavia, Illinois. The firm provided integrated building engineering services for the project's front-end design and civil engineering to completion. The building has a highly flexible, modular laboratory space that has been designed to support the development of accelerator science and technology that has both research and commercial applications. Arup's work is continuing at the campus, where the firm is providing multidisciplinary engineering services on the Integrated Engineering Research Center, which is currently under construction. The 8,000m^2 (26,250ft^2) building is a combination of laboratories, offices and collaborative spaces to support ongoing particle physics research, including DUNE.



9.

9: A number of instruments will be used to measure the rock mass deformations in real time and allow comparison against the 3D numerical design model

Arup will work alongside Fermilab and the excavation contractor (Thyssen Mining) to assess the condition of the rock in the caverns after each blast against the design. Permanent ground support measures, such as long steel rock bolts, will be drilled into the rock mass to retain potentially unstable and loose rock blocks. A layer of shotcrete approximately 100mm thick will be applied to all exposed rock surfaces to seal the ground and ready the space for experiment construction.

Arup will have staff on site full-time during the critical excavation stages of the project to define support types, map the exposed rock and monitor the instrumentation results. A number of instruments, including multiple point borehole extensometers, will measure rock mass deformations at defined depths into the ground in real time and allow for comparison against the 3D numerical design models. Using this system during excavation ensures the ground behaviour and support design will be validated long before the caverns are opened up to their full dimensions.

Ongoing science experiments will be taking place several hundred metres away during the cavern excavation, and these need to remain undisturbed by the blasting and construction process. As part of the completed enabling works, six protective blast doors were installed to provide protection to these experiments, and a 190m (625ft)-long pilot tunnel was formed using the drill and blast excavation method. This tunnel, along with a future raise bore, will provide a new ventilation route from the 4850 to the 3650 Level.

Cooling and ventilating

With no common design code framework for constructing such a facility within the laboratory, Arup used a combination of mining codes and building codes. A critical aspect of the design was the control of the flow of air through the LBNF complex to provide ventilation and smoke control, and for heat rejection purposes. The design includes the addition of new mine doors, with built-in flow regulators, which were modelled using complex air flow models developed by Arup's sub-consultant team and by the South Dakota Science and Technology Authority. The LBNF complex will be connected to the existing exhaust system via the new 366m (1,200ft) vertical raise to the 3650 Level, from where the air is directed to the existing fan plant located at the surface.

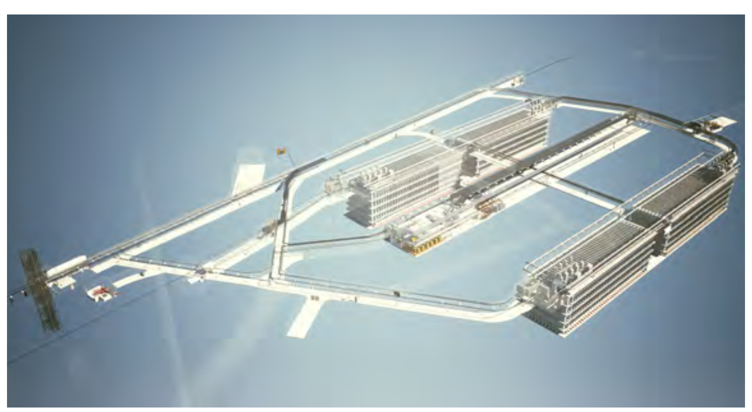
The cooling systems were studied in great detail, and are designed to dehumidify air to prevent condensation on the outside of the cryostats, remove heat from the electronic detector racks and remove waste heat from the nitrogen compressor equipment, which is used to maintain the argon at -184°C (-300°F) so it remains in liquid form. Originally, the nitrogen compressors were intended to be located on the surface to simplify the heat rejection and power infrastructure. However, during the detailed design process, they were relocated underground. This eliminated the need to move existing services in the Ross Shaft to accommodate new piping running down the shaft – reducing the overall construction length by two years. The systems will be connected to 6,500kW of water-cooled chillers located underground, which reject their heat via a purpose-built cooling tower located at the base of the new raise.

Facility infrastructure

Such a large facility has considerable energy needs. The Arup-led team designed the upgrade of the pre-existing substation at the surface so it is able to provide enough power, and of the medium-voltage conductors that run from this substation to transformers located inside the central utility cavern on the 4850 Level. Arup designed the infrastructure feeding the cryogenic equipment that will be used to fill the cryostats with argon. The argon is received in liquid form and vaporised into gas before being sent down the shaft.

Life safety

The fire protection and evacuation strategy required careful consideration due to the nature of the facility, with its depth below ground meaning the evacuation process is not straightforward. Arup used computational simulations to model different fire scenarios. These determined how tenable conditions could be maintained in a fire event, utilising SURF's existing ventilation system, supplemented by additional fans, to exhaust smoke and ensure occupants can evacuate safely under different fire events. Each of the three caverns is its own fire compartment with a separate smoke control system. The design was carried out to a combination of codes, with International Building Codes for the experiment areas and mining codes beyond that. Timed egress studies were carried out to calculate the evacuation time.



10.

10: When operational, LBNF will assist in finding the answers to some of the greatest scientific mysteries

11: The enabling works included the installation of six blast doors to protect the existing scientific areas currently in operation

In the event a fire is detected, the facility occupants will evacuate along the tunnels to either the refuge chambers or either of the shaft stations and travel up the shafts to the surface. With limited capacity in the conveyance – up to 28 people typically, 36 in an emergency – and 15 minutes required for a return trip, the refuge chambers on the 4850 Level provide spaces where personnel can shelter safely in place within a sealed area in the laboratory for an extended period of time (up to 96 hours).

11.

As DUNE uses both nitrogen and argon – two inert gases that displace oxygen – Arup coordinated with the facility teams to provide an early warning system upon detection of a nitrogen or argon leak.

Mining for scientific gold

Creating a modern research campus nearly a mile below ground in an abandoned gold mine originally established in 1877 and added to and expanded over a 125-year period presented quite a design challenge – with scientific work ongoing nearby further adding to the complexity. Arup combined its mining and tunnelling engineering experience with the civil infrastructure design skills required to develop a world-class science and research facility. When complete, LBNF is set to solve some of the biggest scientific questions relating to subatomic particles, expanding the realms of our knowledge.

Authors

Gordon Carrie is the Project Manager for the buildings and site infrastructure (BSI) portion of the project. He is an Associate Principal in the New Jersey office.

Seth Pollak is the Project Manager and Engineer of Record for the excavation contract. He is an Associate Principal in the New York office.

Richard Potter is the lead BSI project engineer. He is an Associate Principal in the New York office.

Josh Yacknowitz is the Project Director. He is the group leader in the Seattle office.

Project credits

Site owner South Dakota Science and Technology Authority
Client Fermi Research Alliance (US Department of Energy)
Construction manager and general contractor Kiewit-Alberici Joint Venture
Excavation contractor Thyssen Mining Inc
Arup sub-consultants:
Civil, structural, mechanical, electrical, plumbing engineers – surface installations TSP; civil engineering RESPEC; surface installations architecture Dangermond Keane Architecture; high voltage systems Power Engineering; underground architect Davis Brody Bond; cost consulting Hollins Consulting; geotechnical engineering McMillen Jacobs Associates; mine ventilation and hydrogeology SRK Consulting; conveyor and crusher design Mincore; underground logistics Hardrock Hickey; shaft consultant GL Tiley & Associates
Geotechnical engineering; plumbing and fire protection; cost/schedule consulting; fire and life safety engineering; IT and communications; mechanical and electrical engineering; mine consulting; structural engineering and tunnelling Arup:
Davar Abi-Zadeh, Francisco Aguirre, Chris Alincastre, Bielka Almonte, James Angevine, Sahil Arora, Stephane Audrin, J Autery, Connor Babbitt, Kaustubh Bakare, Mathew Bamm, John Barrot, Richard Bartholomew, Anthony Bianco, Tony Bisio, Jodi Borghesi, Chloe Bouaziz, Dave Brogan, Cillian Brown, Ian Buckley, Nancy Camacho, Alton Cannon, Ignacio Carrera, Gordon Carrie, David Chan, Dominique Chapman, Lingyi Chen, He-In Cheong, Barry Chisholm, Nancy Choi, Anthony Cortez, Herman Cortez, Craig Covil, Andrew Crutchfield, Haya Daawi, Eric De Oliveira, Ankit Desai, George Donegan, James Doody, Katie Doyle, Nicole Dubowski, Jelena Durovic, Cristian Espadas, Zara Fahim, Steven Fairneny, Neema Faryar, Amanda Faryar, Camilla Favaretti, Adam Finkin, Adrian Finn, Giuliana Galante, Yawo Galley, Bryan Garcia, Jeffrey Garry, Maribel Gibson, David Goldstein, Alex Gomez, Anthony Goulding, Andrew Grigsby, Martha Gross, Eric Guerra, John Han, Chu Ho, Evan Hughes, Anya Huntley, Jon Hurt, Ikenna Ibe, Santiago Icaza, Joanne Iddon, Michael Incontrera, Kendra Jones, Onur Kacar, Deepak Kandra, Navjot Kaur, Joseph Kim, Galen Kirkpatrick, Vadim Klugman-Kovalenko, Jacob Koshy, Jaewook Kwon, Alvin Lachhman, David Lambert, Craig Leonard, Danny Lin, Dennis Lowenwirth, Haiyan Lu, Jeremy Macht, Cecy Martinez, William Masters, Sarah McDowell, Andrew Mertz, Anna Montoya-Olsson, Chris Muller, Kirk Nosho, David Okada, Austen Paris, Jay Patel, Lisa Pazzani, Richard Petrey, Hilary Pherribo, Seth Pollak, Richard Potter, John Powell, Sara Qais, Andy Quinn, Parisa Rajaei, Guilherme Rebello, Ryan Redican, Shannon Rice, Julian Safar, Kirsten Salmins, Natalia Sanabria, Sarah Sausville, Joe Saverino, Lauren Scammell, John Scavelli, Eric Seck, Luv Sehgal, Juan Manuel Serrano, Samantha Sharma, Ken Shih, Ria Singh, Tom Smith, Kevin Snagg, Eugene Stolberg, Kristen Strobel, Art Suhakou, Fabio Malheiro, Carolina Tello, Matthew Terracciano, Gordon Thompson, Chanpreya Thou, Colm Tully, Eric Van Laar, Joshly Varghese, Foteini Vasilikou, Alessandra Vecchiarelli, Juliet Walker, Guillaume Weingertner, David Weiss, Andrew Wise, Philip Wood-Bradley, Yuanli Wu, George Wu, Wei Xin Lin, Josh Yacknowitz, Haoran Zhang, Asadullah Ziaei.

Image credits

1, 4, 7, 9–11: Arup
2: Matthew Kapust/SURF
3, 5, 6, 8: Fermilab

In good hands

Along with the British Red Cross, Arup has developed a resilient, effective handwashing apparatus that also promotes dignity

Authors Stephen Philips, Iñigo Ruiz-Apilánez and Martin Shouler

According to the UN High Commissioner for Refugees, there are 40.8 million internally displaced people in the world today, 21.3 million refugees and 3.2 million asylum seekers. Around a third of these individuals are living in informal settlements, where diseases such as cholera, pneumonia and diarrhoea can spread quickly. Handwashing with soap is an effective way of preventing the spread of such diseases, with evidence showing that it can reduce the risk of infection by up to 50% in post-emergency situations.

The British Red Cross wanted to develop a handwashing unit for emergency use and approached Arup to help create one, with the brief that the unit had to be centred around the user, portable and resilient. Along with the London School of Hygiene and Tropical Medicine, Arup developed the Jengu handwashing unit, which has been dispatched to informal settlements and – since the outbreak of COVID-19 at the start of 2020 – also used around the UK.

First steps

Arup's annual Community Engagement Global Challenge Fund is available to Arup staff and partners for projects that look to solve some of the biggest challenges of our time, with the aim of developing innovative, scalable solutions that address systemic challenges. The team working on the handwashing unit

1: The Jengu handwashing unit is robust, easy to fabricate and user-friendly

1.

2.

presented their ideas and were granted funding. Arup's product design, international development and human factor teams, as well as material and water engineers, were involved in the project.

The first step in developing an effective handwashing unit was conducting desk and field research. Arup looked at the various handwashing units used in informal settlements around the world to weigh up which designs seemed to be most popular and which were most effective. The team reviewed over 30 different units, giving each scores across several categories. They also went out into the field, visiting Kyangwali Refugee Settlement in Uganda. This is a long-established, well-organised settlement that is currently home to many refugees from the Democratic Republic of Congo.

One of the main handwashing units used worldwide is the 'Tippy Tap'. This is simple and easy to set up: the structure is created by positioning two branches upright in the ground and laying a third branch between them; this third branch is threaded through a water bottle handle, which is thus suspended above the ground. A string attached to the water bottle runs to a piece of wood on the ground, allowing it to be tipped up and for the water to fall. Although easy to construct, the flow of water can be unsteady and, with no basin, wastewater falls to the ground, where it can potentially attract mosquitos. Tippy Taps are also not particularly robust, and soap is generally not provided.

Raised tanks with taps are another common form of handwashing unit. As with the Tippy Tap, these are easy to source and set up. However, as the water tank is raised, it must be refilled at a height. The basin that catches the water is low, meaning that most adults have to bend down to use the unit. Having a tap creates potential for contamination, as users have to touch the tap before and after washing their hands. And the tanks need to be placed on level surfaces so that they don't topple over; in informal settlements, it can be hard to find appropriate level ground.

Arup's behaviour change and product design specialists conducted interviews with refugees in Kyangwali, both young and old, to find out more about their handwashing habits and the kind of designs that would be most familiar to them and therefore likely to be used. Arup knew it was important to create a unit that would be globally recognised and found through its interviews that the typical sink with tap would be most familiar.

Refining the design

Following the desk and field research, Arup knew which elements were essential to the handwashing unit. It should not be gravity-fed, as these models tend to be difficult to refill. The unit should allow wastewater to be drained and should not have a tap, to remove a potential contamination point.

Water supply was a key consideration. Jerrycans are ubiquitous in many parts of the world, used extensively for water transportation and storage. To avoid a situation where people were having to refill a top tank, the team wanted to create a unit that could be supplied directly from a jerrycan or larger container. Logistics and fabrication were two other key questions. The unit had to be easy to deploy and easy to construct anywhere in the world. The ability to fabricate the units locally was important too. Arup learned that skilled metal fabricators tend to be found worldwide, and so decided that a metal handwash unit would be an apt choice.

Arup spent some time devising the best way to deal with wastewater from the unit. It was designed so that water can be drained away, either into a drain or into a soakaway (where an area of ground is excavated and a tube from the unit inserted, before soil and loose material is returned over the top).

The British Red Cross requested that the units include a mirror and a space for soap. Best handwashing practice involves using soap and water, not only to remove pathogens from your hands but because using soap improves the handwashing experience and encourages good practice: it leaves a pleasant smell and gives a feeling of cleanliness.

The mirror was deemed an essential part of the unit. Research conducted by the London School of Hygiene and Tropical Medicine found that the inclusion of a

3.

2: Raised tanks are often used in handwashing units

3: The 'Tippy Tap' is another common form of handwashing unit in informal settlements

4.

5.

4–5: Arup developed a number of design concepts, which the team presented to a workshop of NGOs and WASH practitioners

mirror made people more likely to wash their hands. A mirror acts as a prompt, encouraging people to use the unit because they can also check their appearance at the same time. It also promotes human dignity in an environment where too often this can be seen as an optional extra.

Taking these factors into consideration, Arup refined and developed its designs and held a workshop, with attendees including NGOs and WASH (water, sanitation and hygiene) practitioners. At the end of the workshop, participants voted on their preferred unit.

Creating the Jengu handwashing unit

Once the final design was selected, Arup carried out in-depth CAD modelling using SolidWorks software. This enabled drawings of every component to be generated and sent to fabricators. The handwashing unit is open-source design, meaning it can be used by anyone around the world.

The basin is circular and shallow, as with a typical sink. In their field research, the Arup team had found that washing-up bowls were widely available locally, and so a unit in which a bucket or washing-up bowl could be used would provide people with more choices. A shallower basin also prevents splashback and allows users to see the dirt wash away from their hands. The basin is circular, as it makes handwashing a communal activity and means parents can teach children good handwashing practice because they're able to use the unit together.

The unit has space at the side for either liquid soap or bar soap – whichever is preferred or more easily available in the region the unit is deployed. In informal settlements, soap theft is common, so the soap can be secured to the unit, either by using a cable threaded through a bar of soap or by attaching a bottle to the side of the unit. The foot pump provides just enough water for users to wash their hands, helping to reduce water wastage. The faucet is curved and positioned so that the unit is suitable only for handwashing, not for filling containers.

The unit comes in two heights: one that is suitable for adults, and another at a shorter height so that children find it easy to use.

Arup has started development of a unit for use by people of reduced mobility. For wheelchair users, the legs of the unit are positioned to one side to allow them access to the basin. For individuals who have lost their legs, the unit can be adapted so that they can support themselves on it using their arms and can pump the water using the flat of their forearm. Arup is continuing to develop the design for other forms of reduced mobility, with the aim that all people will be able to use the unit with ease.

Deployment

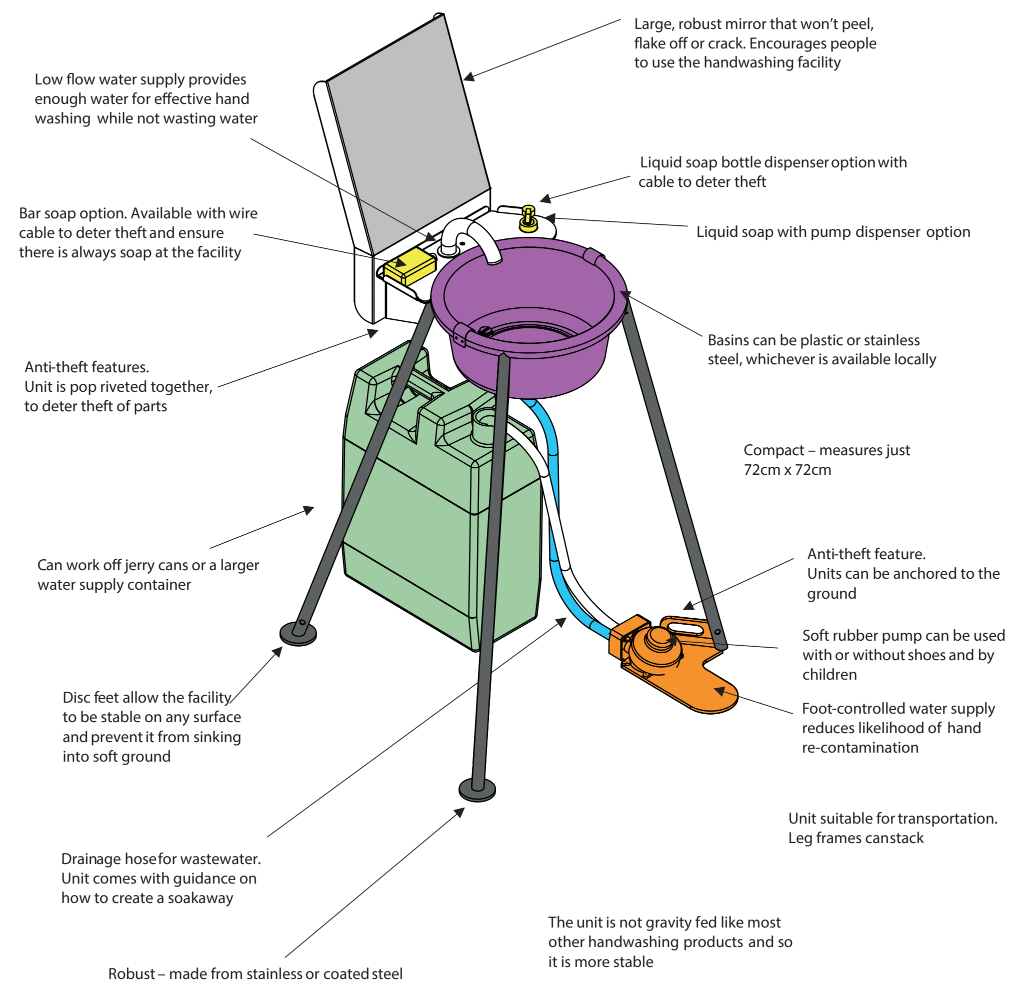
Prototypes were manufactured by UK fabricator Aldermans, and the Jengu handwashing unit was then tested in the field, first by the British Army during their training manoeuvres on Dartmoor. Arup's human factors team received feedback from the troops about their use of the product, allowing the team to understand more about how it would actually be used and what was and wasn't working. Prototypes were also tested outside Arup's London office in Maple Place in order to see how children would interact with the unit, and then in the Kyangwali Refugee Settlement.

Twenty units were deployed to Uganda and Haiti. Then, at the start of 2020, the COVID-19 pandemic broke out. One of the easiest ways to prevent infection is washing your hands regularly. Arup had 50 units manufactured in Plymouth to be deployed around the UK. Thirty went to schools, twelve to homeless shelters, six to community organisations, one to Newcastle County Council and one to a mobile mountain rescue centre. This deployment has demonstrated the unit's flexibility and how easily it can be used in varying circumstances.

The Jengu handwashing unit is a robust, easy to fabricate and user-friendly unit that encourages handwashing and makes it easier for people in many different circumstances to maintain handwashing hygiene, not only preventing the spread of disease but helping those in tough situations to create a semblance of a normal routine. Jengu is an open-source blueprint design, meaning it can be manufactured by any company or individual with the right materials and equipment (the blueprint can be found at jengu.org.uk). It doesn't require any plumbing and so can be easily set up in challenging environments. The unit has had great success so far and looks set to be used ever more widely. Save the Children has commissioned 250 units to be manufactured and deployed to informal settlements in Nairobi, Kenya, and Arup will be investigating how to manufacture these units locally. In addition, the Red Cross is also deploying units in Sierra Leone and Lebanon.

6.

6: The Jengu handwashing unit can be adapted so that it can be easily used by children and people with reduced mobility



7.

8.

7: Every element of the Jengu handwashing unit was designed to be user-oriented and resilient

8: A woman uses a prototype Jengu unit in Kyangwali Refugee Settlement

9: During the COVID-19 pandemic, units were deployed around the UK, including to West Lea School in north London

9.

Authors

Stephen Philips led the research, concept design and detailed design phases of the project. He is Arup's global product design leader and an Associate in the London office.

Iñigo Ruiz-Apilánez was the Project Manager. He is a senior civil engineer in Arup's International Development team in the London office.

Martin Shouler was the Project Director. He is an Associate Director and leads Arup's water business in the London office.

Project credits

British Red Cross

London School of Hygiene and Tropical Medicine

Arup:
Lucie Barouillet, Douglas Brierley, Sara Candiracci, Jo da Silva, Eleanor Earl, Martin Findlay, Sophie Fisher, Miriam Kennedy, Chris Miller, Paula Morcillo de Amuedo, Callum Newman, Tom Norton, Mei-Yee Oram, Stephen Philips, Caroline Ray, Max Resnick, Iñigo Ruiz-Apilánez, Martin Shouler, Maria Sunyer Pinya, Roman Svidran, Aliki Vaina, Peter D Webster.

Image credits

1, 6, 7: Jengu/Arup
2–5: Arup
8: Greg Rose
9: West Lea School

Game changer

With a constrained 12-month turnaround, Arup adapted a stadium to create a multipurpose venue used year-round

Authors Jake Cherniayeff, Andrew Johnson, Hannah Lazenby and Xavier Nuttall

In late 2018, Tennis NSW approached Arup with a challenge – was it possible to fully enclose the Ken Rosewall Arena in 12 months?

In 1998, Arup engineered the award-winning Ken Rosewall Arena, the central court of a new tennis precinct constructed to host the Sydney Olympics tennis events. Although the original design won prestigious awards, the open-air stadium lacked versatility in legacy mode and soon became underutilised, hosting only one major event annually in the lead-up to the Australian Open in Melbourne.

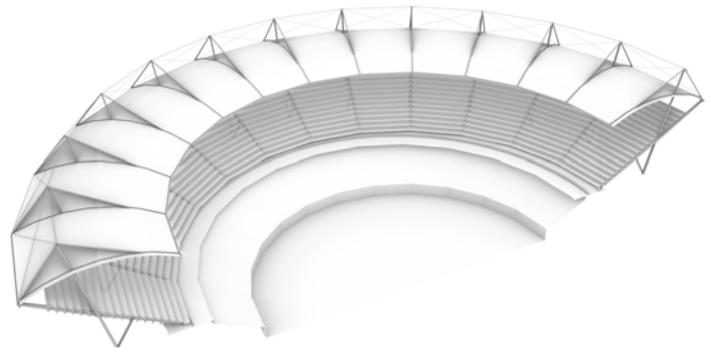
Twenty years later, Tennis NSW secured the rights to host the inaugural ATP Cup in January 2020; however, the Ken Rosewall Arena needed to be transformed in order to hold the event. A major requirement was to provide full roof coverage over the court, while still maintaining the stadium as an outdoor venue (to meet the International Tennis Federation's event requirements). The new roof offers protection from inclement weather, minimising any disruption to play (which would impact the tournament schedule, broadcasters and ticket sales), and provides a more comfortable environment for players and spectators.

Tennis NSW returned to Arup for a creative solution. The team enabled the upgrade to be designed, constructed and commissioned within 12 months – including transforming the stadium into a multi-purpose venue to facilitate netball.

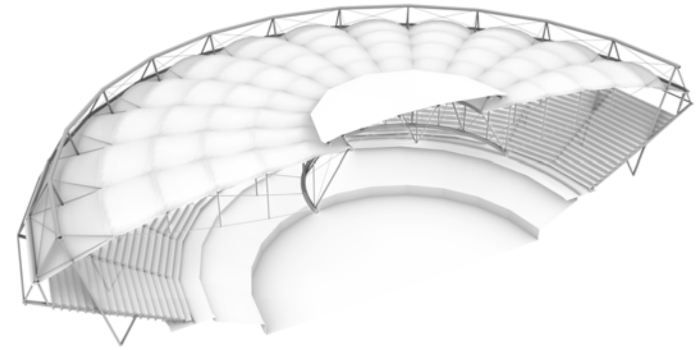
Arup was responsible for structural, civil and geotechnical engineering, building services, building physics, fire safety, sports lighting, access and maintenance, and acoustic and audio-visual services

1: The Ken Rosewall Arena was upgraded, including the creation of a new enclosed roof, in only 12 months

1.



2.



3.

from concept to completion. Cox Architecture and Fabritecture were key design partners. A W Edwards was the managing contractor.

An innovative roof solution

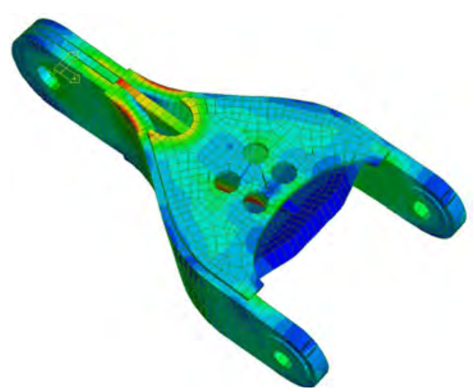
The circular form developed for the Olympic arena was fundamental to the original design, and retaining this circular philosophy was key to unlocking an effective new roof design. Arup's solution was to remove the existing perimeter canopy roof and replace it with a 100m-diameter self-contained radial cable net structure, clad with PTFE fabric. The radial cables, which overlap to minimise the overall height of the structure, are restrained by twin internal tension and perimeter compression rings, the latter supported on the existing columns and foundations. The first roof of its kind in Australia, this lightweight solution replicated the existing roof load path through the superstructure, leading to only a minor load increase on the existing piles, with calculations demonstrating that the subsequent settlement increase could deliver the additional required geotechnical capacity. Avoiding new foundations was critical; the 12-month design, approvals and construction period did not allow for the possibility of new piled foundations disturbing the originally contaminated land that had been remediated and capped during construction of the Olympic arena.

With only three months available for the design process, the structural team used an automated digital workflow to design the roof. This parametric approach generated the roof geometry and staged structural analysis models of the existing structure and new roof, and set out the pre-camber and fabrication geometries. A collaborative multidisciplinary module was built into the Grasshopper parametric design script. This enabled the structural team to fine-tune the geometry of the central oculus – the raised roof section 25m in diameter – with Arup's building physics and fire engineering teams. It was possible to seamlessly integrate the natural ventilation and smoke management requirements with the geometry of both the primary and central raised oculus roofs. The digital workflow enabled the team to achieve the extremely fast programme by avoiding a traditional drawing delivery; instead, Arup developed and delivered connections in a 3D environment, which formed the basis for the contractor shop detailing.

Arup's understanding of the original structural strategy and construction sequence informed its solution for the removal of the existing perimeter roof and the design of the new roof. Utilising this knowledge, the team developed the form and stiffness of the new roof structure such that final prestressing of the radial roof cables replaced the support for the upper bowl structure originally provided by the tension ring of the now-demolished roof. The final 'neutral' condition was achieved during construction by propping and hydraulically lifting the raker tips to destress the existing ring tie, lowering the rakers and, finally, prestressing the new roof – which in turn lifted the rakers from the temporary props back to their original position.

Time histories were used in wind tunnel testing to generate simultaneous pressure coefficients across the roof surface, with

4.



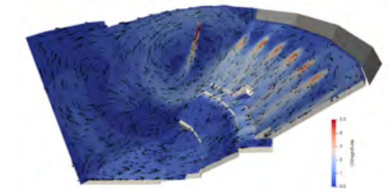
5.

2–3: The existing perimeter canopy roof was removed and replaced with a self-contained radial cable net structure

4: Arup developed and delivered connections in a 3D environment to expedite the fabrication process

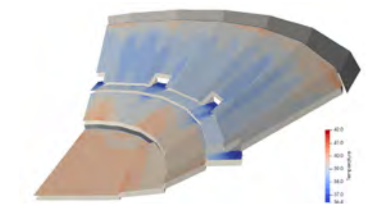
5: An automated digital workflow was used to design the roof

6.

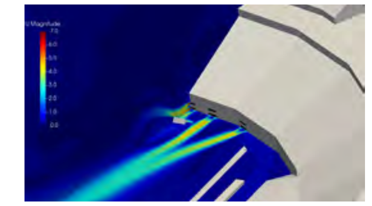


7.

8.



9.



10.

these results used to alter the roof geometry and minimise net downward pressures – critical in reducing additional vertical loading on the existing structure and piles. To further future-proof the venue, discrete tangential bracing was integrated into the design to meet seismic design code changes introduced since the arena's original construction. Fire engineered solutions were used to assess the supporting steel frame and omit the need for fire protection, creating time and cost savings.

Mixing indoor and outdoor

While the initial plan was for the stadium to be used only for tennis in 'outdoor' mode – the ATP Cup is an outdoor event – shortly after the project began the venue owner, Sydney Olympic Park Authority (SOPA), proposed that the stadium be configured to also host 'indoor' netball games year-round. This needed to be done without converting fully to an indoor arena, as planning and building code reasons precluded that change. The transformation into a multipurpose venue altered the functional, technical and environmental requirements significantly – with solutions required to accommodate thermal comfort, glare control, and moisture thresholds necessary for international netball and broadcasting. These requirements played a major part in shaping the project's final technical solutions and outcome.

Collaborative working sessions were held with key stakeholders including Tennis NSW, Tennis Australia, Netball NSW, SOPA, host broadcasters and Channel 9, presenting the live 3D model of the design as it developed to allow the wider project team to understand the new aspects of the building and its functions. With the parametric workflow already set up, client feedback could be incorporated into the design in real time.

Creating an ambient atmosphere

The addition of the roof required a new ventilation and fire engineering strategy, as it was necessary for the arena to be naturally ventilated in both tennis (open) and netball (enclosed) modes. Once it was decided that the stadium would host both sports throughout the year, thermal comfort was a key aspect of the design. The venue's location – in western Sydney – experiences extreme temperatures of up to 45°C, coinciding with up to 60% relative humidity between November and March. Arup conducted extensive thermal analysis to understand the environmental conditions for playing sports throughout the year. How hot would it get in summer for the tennis players? And in winter when teams were playing netball, how might condensation impact the space, and how could this be prevented on a cool night?

Tennis has a great deal of flexibility when it comes to playing in hotter weather, but netball has strict heat policies. The possibility of adding an air-cooling systems solution for the arena in enclosed mode was limited due to two factors: statutory restrictions on energy supplied for cooling an unsealed and uninsulated building, and the preference for a passive environmental solution.

6: The new structure was clad in PTFE fabric

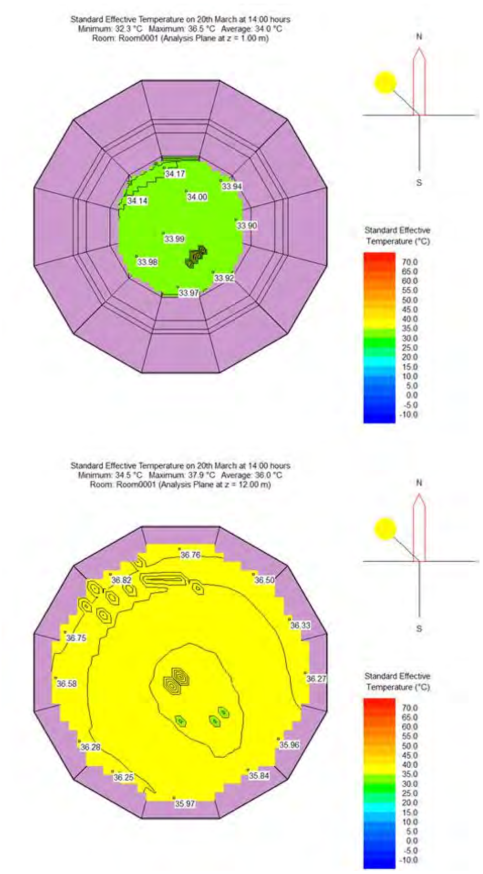
7: Contours of velocity at 1m above the ground

8: Spot cooling CFD studies, court-level temperatures

9: Contours of temperature at 1m above the floor

10: Spot cooling CFD studies, high variance velocities restricted to court edges

11: Thermal analysis was conducted to ensure conditions were comfortable for playing sport year-round



11.

12.

12: Automated hydraulic folding doors 4m in height can be opened and closed as necessary

13: Arup drew on its knowledge of the arena's original design strategy to develop the ultra-lightweight roof

The raised central oculus provides a 3m-high louvred opening around the full perimeter of the pop-up roof. Combined with the 4m-high opening at the back of the bowl, this was critical in the provision of sufficient free area for natural ventilation and smoke extraction. Hydraulic folding doors 4m in height run the full perimeter of the bowl and have individual automated controls to provide the open and enclosed modes required for the two sports. This allows the external/environmental aspects of glare (affecting play and broadcasting) and wind-driven rain for netball to be effectively managed. With the doors closed, a 900mm-wide horizontal slot remains for ventilation.

Arup used computational fluid dynamics (CFD) to model air movement within the roofed stadium, in both open mode for tennis and enclosed mode for netball, and in combination with thermal modelling, to assess spectator and player comfort. Using a mix of analysis and strategic placement of smoke separation, the fire engineering team determined that the proposed natural ventilation strategy would be sufficient to clear smoke from the arena without the requirement for an active smoke exhaust system within the lightweight roof.

To manage extreme conditions of high temperature and/or humidity and low wind speed, a solution was developed with Tennis NSW and SOPA to provide freestanding, portable, low-load air conditioning units at courtside during the warmer months, operated only when extreme conditions demand. In-line fans were installed around the perimeter for thermal comfort. This overlay system of semi-permanent design for the court cooling strategy and backup power supply is utilised for events in the warmer months only, reducing capital, operational and maintenance costs. This strategy means that the arena remains predominantly naturally ventilated. Arup also specified a designated controls system that gives the client a high level of autonomy in managing the building.

Acoustic simulation

Arup's acoustic team developed acoustic models of the arena and presented the predicted acoustic environment to stakeholders, professional tennis players and client representatives in the firm's SoundLab in the Sydney office. This allowed them to experience immersed simulations of the reconfigured arena. The team developed auralisations of scenarios using sound sources from capacity crowds, PA vocal announcements, music/performance and rain noise from the uninsulated PTFE roof. This was a valuable exercise for Tennis NSW, which was able to qualitatively experience the anticipated acoustic conditions in the arena, allowing it to make informed decisions on treatment and audiovisual overlays.

13.

A high-speed digital approach

There was only 12 months from project conception to completion, with the inaugural ATP Cup an immovable date. Arup worked collaboratively with the roof sub-contractor from the start, aligning and proving the firm's proposed construction methodology for both the removal of the existing roof and construction of the new roof. Procurement of the wire rope and PTFE fabric was critical – both materials have long lead times – and within the first week Arup committed to a quantity and diameter, and the order was placed. The team then had only three months to complete the detailed design and develop the fabrication geometry of the roof structure. Creating an efficient digital workflow was crucial. It was agreed that the structural design would be delivered to the client in a 3D modelling environment, without 2D CAD drawings. Arup used Rhino, a 3D modelling programme, linked with Grasshopper and the firm's form-finding structural analysis software GSA, to allow the structural geometry and architectural requirements to be optimised within the tight timeframe. The Rhino geometry also formed the foundation for the connection design, which was detailed by Arup in 3D and issued to the shop detailers for direct preparation of the roof fabrication drawings and to the architects for coordination and visualisation.

Building services were closely coordinated and set out in the 3D model during detailed design to allow early procurement of the structure before appointment of the building services sub-contractors. Cabling and services within the bowl were closely considered and minimised to accentuate the lightweight roof structure and avoid shadowing on the court surface.

The digital workflow meant the design could evolve to incorporate changes, such as the client request for additional court clearance above ATP minimum to match Grand Slam venues, raising the perimeter of the roof based on the players' desire to see more sky between the bowl and roof at the eaves, and the additional roof loading from the netball monitor scoreboard. The workflow enabled the design to be rapidly reconfigured and structurally optimised parametrically. The digital design and delivery environment was intrinsic to the project being delivered on time.

14.

15.

An improved arena

The project was delivered as planned for the inaugural ATP Cup, with the venue transformed through the addition of a new roof, a full building services upgrade, refreshed seating, upsized configurable video screens and anti-glare LED sports lighting. Systems were also put in place to allow broadcasters to 'plug and play' their equipment without requiring significant additional cabling or power requirements. The design team maximised the reuse of the existing venue, and in regenerating and reconfiguring the structure through high-quality engineering and construction-based solutions, Arup helped created a multi-purpose venue with less than 30% of the embodied carbon of a similar new build.

Arup's contribution to the success of the redevelopment lay in its knowledge of the original design strategy and its skill in utilising the stadium's original form to conceive an ultra-lightweight roof that alleviated the need for new foundations and significant strengthening of the existing structure; its integration of digital workflows to optimise the design and improve the speed of project delivery; and its consideration of buildability. All provided the basis for the firm to make sound decisions and judgements to the benefit of the project and the client.

Ken Rosewall Arena is now used year-round, as an anchor venue for the ATP Cup, and as the home of the NSW Swifts and GIANTS Netball teams. It is an excellent example of repurposing an older building to give it a new lease of life.

14: The 4m-high hydraulic folding doors run around the perimeter of the arena

15: The upgraded arena was completed in time for the inaugural ATP Cup and is used for sporting events year-round

Authors

Jake Cherniayeff was the Project Manager and led the building services design. He is a senior engineer in the Sydney office.

Andrew Johnson was the Project Director. He is a Principal in the Sydney office.

Hannah Lazenby worked on the structural design. She is an engineer in the Sydney office.

Xavier Nuttall was the lead structural engineer for the roof design. He is an Associate in the Sydney office.

Project credits

Client Tennis NSW
Architect Cox Architecture
Managing contractor A W Edwards
Roof contractor Fabritecture
Structural engineering, building services, fire safety, acoustics, building physics and thermal comfort, acoustic, civil and geotechnical, access and maintenance, sport lighting, audio-visual Arup: Rowan Boltman, Tom Brickhill, Bonnie Chang, Jake Cherniayeff, James Cho, Katelyn Commerford, Jethro Dickens, Johnny Gian, Oliver Gibson, Phillip Greenup, Sina Hassanli, Daniel Hinds, Guy Hopkins, Petunia Huang, Vincent Hurley, Andrew Johnson, Jorg Kramer, Henry Lam, Hannah Lazenby, Ben Moore, Alistair Morrison, Owen Myers, Xavier Nuttall, Tiffany Or, Livia Renhe, Tom Salkild, Len Samperi, Adam Segall-Brown, Mathew Simon, Yuanyuan Song, Qian Wang.

Image credits

1, 12–14: Martin Mischkulnig
2–11, 15: Arup

1.

New connections

Ireland's longest bridge improves regional, national and international connectivity

Authors Mike Evans, Cian Long, Alfonso Ramirez and Marcos Sanchez

The opening of the Rose Fitzgerald Kennedy Bridge in January 2020 completed a critical new section of Ireland's N25 road, a crucial component of the country's transport infrastructure. The new dual carriageway route includes 14.9km of national road as well as the new bridge, which combines cable stay and pier support and provides breathtaking views of the Barrow River area. At 887m in length, the bridge is impressive in scale and slenderness. It is Ireland's longest bridge, with the two main 230m spans making it the longest concrete extradosed bridge in the world.

This new transport link forms part of the strategic N25 New Ross bypass in County Wexford, providing a safer route and improving traffic flow in the town and the surrounding area. New Ross, around 25km upstream from the sea, used to be the last fixed crossing over the River Barrow before the sea and attracted significant traffic on the single carriageway through the town, leading to frequent congestion. Following the opening of the Rose Fitzgerald Kennedy Bridge, shorter and easier to predict journey times are now benefiting commuters in the area, improving quality of life and supporting economic growth in the region.

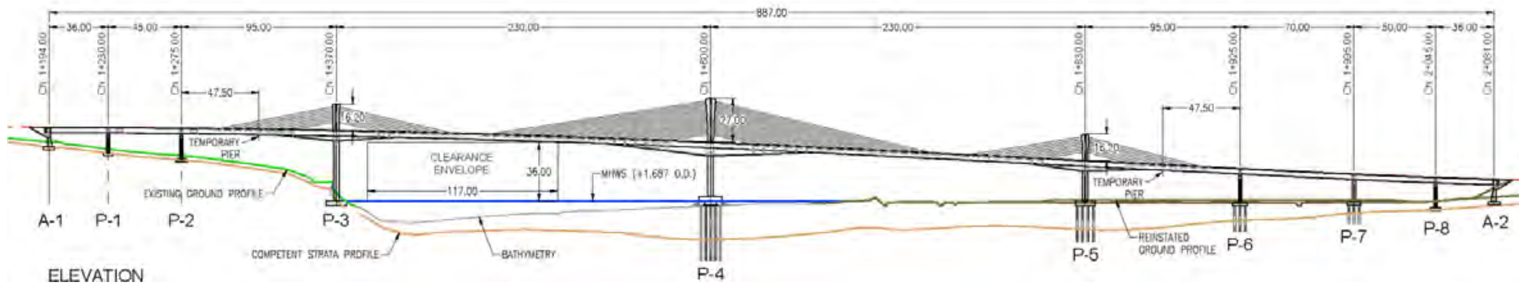
The N25 road and bridge contract was tendered as a public–private partnership scheme. The joint venture (JV) of BAM Civil Ltd. and Dragados Ireland Ltd. was awarded the contract, with construction beginning in early 2016. Arup was appointed by the JV as the lead design consultant for the national road, and the firm partnered with Spanish bridge specialist Carlos Fernandez Casado (CFC) on the bridge design.

1: The Rose Fitzgerald Kennedy Bridge connects Pink Point in Kilkenny with Stokestown in Wexford, providing a crucial crossing over the Barrow River

Arup designed numerous features along the 8.7km of N25 dual carriageway, 5km of N30 dual carriageway and 1.2km of N30 tie-in single carriageway. The design included a grade separated junction, three at-grade junctions, a bridge over the disused New Ross/Waterford railway line, 11 local road bridges and 13 minor structures. Arup provided highway, bridge and geotechnical engineering design services, as well as environmental consultancy, hydrodynamic modelling, site supervision and project supervision for the design process services.

Extradosed bridge

A critical component of the route was the design and construction of the Rose Fitzgerald Kennedy Bridge, connecting Pink Point in Kilkenny to Stokestown in Wexford at a location where the Barrow River is 300m wide. The three-tower structure is an extradosed bridge: it combines the main elements of both a prestressed box girder bridge and a cable-stayed bridge. The extradosed design uses much shorter towers than a cable-stayed bridge and a significantly shallower deck than a box girder, resulting in a bridge that is less obtrusive and therefore more sympathetic to its surroundings. At 36m above the mean high-water spring tide in the river, the bridge provides the required 120m-wide



2.

navigational channel clearance for shipping into the port of New Ross.

With the east bank of the river lower than the west, the bridge's vertical alignment has a 5% change in slope. The bridge consists of nine spans: the approach spans vary from 36m to 70m and the four main spans comprise two 95m and two 230m spans. The central 650m that crosses over the river and floodplain is spanned with only three supports.

The planning constraints and contractual conditions set out the number, location and height of the towers, the navigation clearance, and the requirement that concrete be used for the deck and towers for durability reasons. These constraints limited the detailed design changes allowed, but Arup carried out a value engineering exercise identifying a number of areas where cost savings could be made. Small adjustments in the vertical and horizontal alignment optimised the longitudinal behaviour of the bridge and reduced the overall length by 8m. The number of supporting cables was reduced, with a single set of cables used to support the deck instead of pairs or three cables in parallel. In addition, Arup incorporated precast concrete panels in the deck cantilevers to minimise the cross-sectional weight. All these changes were focused on achieving a balanced span arrangement and a cross-section that was as narrow as possible in order to reduce the impact of the self-weight, given that a full concrete deck was required.

3.

4.

2: The three-tower extradosed bridge has only three supports at its central 650m stretch

3: The bridge's vertical alignment has a 5% change in slope, as the west bank of the river is higher than the east

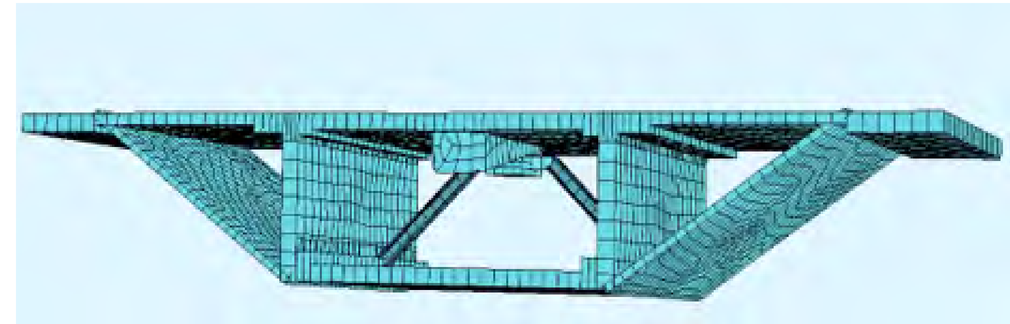
4: The deck cross-section is a single 8m-wide prestressed in-situ concrete box

Deck

The bridge deck carries a dual carriageway and comprises post-tensioned in-situ reinforced concrete trapezoidal box sections, with widths varying from 20.9m to 23m. The cross-section is a single 8m-wide prestressed in-situ concrete box with 6.5m-long cantilevers on either side. This is supported by precast panels to reduce the cantilever length, minimise the self-weight of the deck and provide a smooth appearance. The shallow deck is 3.5m deep at mid-span, 8.5m over the central tower and 6.5m over the side towers.

The anchor of each cable produces significant bending on the top slab of the deck, meaning that the transversal behaviour had to be carefully investigated. In order to analyse this, different 3D finite element models were developed using SOFiSTiK and Abaqus. This resulted in transversal post-tensioning of the deck, in addition to prestressing longitudinally and prestressing of the cables. Internal steel props, which connect the central anchor to the webs of the deck at their bottom corners, were also used to distribute the transverse load.

As the central tower is located close to the mid-point of the bridge longitudinally and receives a larger vertical load, a monolithic connection between the deck and the tower at that location was used, with a configuration of pairs of pot bearings at every other support line and four bearings used at the abutments.



5.

5: SOFiSTiK software was used to develop 3D finite element models to analyse transverse behaviour in the deck

6: The bridge abutments are supported on spread foundations

7: The bridge central support is founded on a 27m x 14m x 4.5m pile cap

Owing to the durability requirements and elevated compression loads due to the shallow cable arrangement, and with the aim of minimising the deck depth to reduce self-weight further, high-strength concrete was used to construct large sections of the deck box. C80/95 concrete was used in the main spans, C70/80 in part of the back spans and C50/60 for the approaches.

Cables

During the design development stage, Arup reduced the number of cables transversally and also incorporated saddles for the cable to run continuously over and through the towers. This arrangement allowed the towers to be reduced from 4.3m x 2.6m on plan from the tender design to 4.3m x 1.6m, meaning that the overall width of the bridge could also be reduced.

The maximum cable length during construction was 278m between active anchors in the deck. The cables are arranged in a harp configuration, with a shallow angle to the deck of between 9 and 11 degrees, and a spacing of 6.5m in the deck and 1.1m in the towers. There are eight cables in the lateral towers (which both rise to a height of 16.2m above the deck) and 18 cables in the central tower (which is 27m above the deck). Each cable in the approach spans at the lateral towers has 109 strands, with 124 strands from the central tower. The individual strands were coated with a black high-density polyethylene (HDPE) sheath and provided with a petroleum wax protective filler in the interstices between the wires comprising the strands. The cables were then enclosed by an outer HDPE protective pipe. The cables went through a full-scale 2 million cycle fatigue test in a laboratory in Chicago, one of only two labs worldwide that can test cables of this size.

Wind and fire analysis

The design required that the bridge be able to remain open under the maximum wind conditions resulting from a five-year return period. Specific wind studies were carried out on the bridge design, in addition to the conventional wind studies on the overall bridge stability. These additional studies were experimental, using a wind tunnel, and numerical, taking into account the results of the wind tunnel tests. They demonstrated the wind effects on both the structure and the vehicles on the bridge. As a result of this analysis, it was proven that no specific wind shield was required at the edges of the bridge, with only a small wind shield panel around the towers necessary.

The bridge design also included an assessment of a 50MW fire on the bridge and the resulting impact on the cable system. Fire modelling and non-linear structural analysis were carried out to demonstrate the capacity of the structure against progressive collapse. Following this assessment, the only additional requirement in the final design was the installation of thermal blankets around the lower part of the cables as a protective measure.

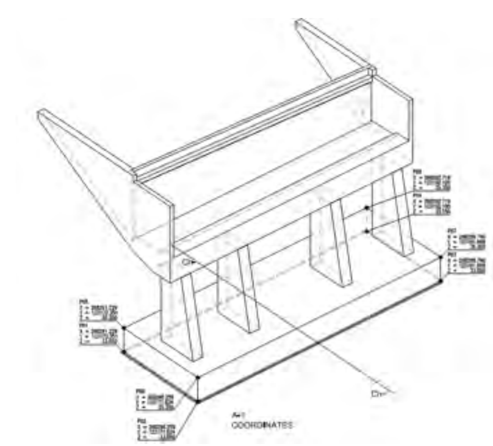
Foundations

Five of the bridge piers are supported on piled foundations, with the remaining three, along with the bridge abutments, using spread foundations. The central support for the bridge is founded on a

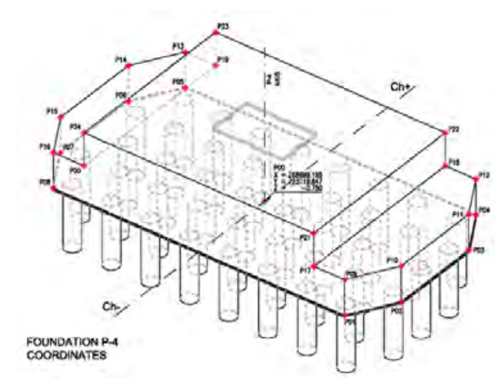
Awards

2020
Association of Consulting Engineers of Ireland
Overall Project of the Year

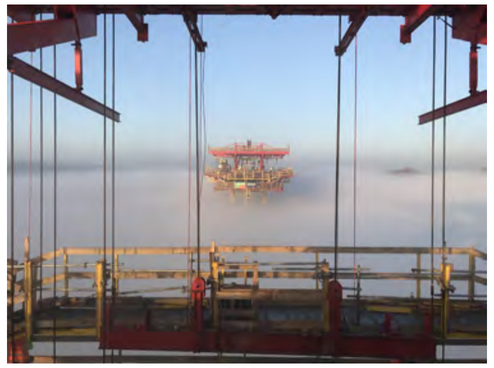
Engineers Ireland
Engineering Infrastructure and Buildings Joint Winner
Engineering Excellence Digital Series Winner



6.



7.



8.

9.

27m x 14m x 4.5m-deep pile cap, supported by 42 rotary-bored piles 1.2m in diameter and 31m long. The support is 70m from the riverbank – outside the navigational channel, but within the tidal range. The design requirements included the assessment of an impact load on the substructure from a 6,000-deadweight tonnage ship travelling at eight knots – a load of up to 17MN. The detailed analysis considered the configuration of the ground conditions and the dissipation of the energy of the ship while approaching the foundation, along with the non-linear behaviour of the soil-structure displacements during the impact scenario. A small rock revetment, which also serves as scour protection, was placed to reduce the forces in the piles to within their design limit.

With the Barrow a candidate Special Area of Conservation due to it being home to rare habitats and species, and the River Barrow estuary a proposed Natural Heritage Area, Arup carried out 2D hydrodynamic modelling on the river for the construction and completed structure stages. This analysis helped ensure minimal disruption to the waterway and the river ecosystem.

8: Four form travellers were used to construct the deck for the main spans in 6.5m sections

9: Two travellers started from either side of the central tower, and two started from the lateral towers

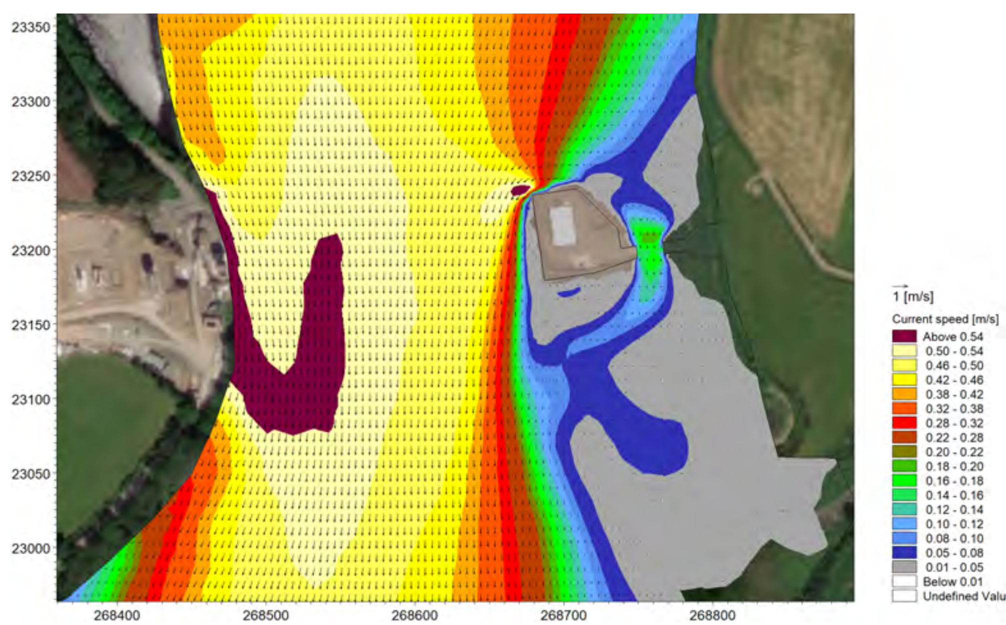
10: Arup carried out 2D hydrodynamic modelling on the river to ensure minimal disruption to the waterway and ecosystem during the construction and completed structure stages

Construction

Climbing formwork was used for constructing the bridge piers, which range from 10m to 39m in height and are typically 6m x 2m on plan. The larger 6m x 3m central pier, due to its location in the river, contains stainless steel reinforcement for durability purposes. The deck for the main spans was constructed in 6.5m sections using four form travellers. Two travellers progressed using the balanced cantilever method from either side of the central tower, and the other two started from the lateral towers. This method allowed all construction activities to take place without interfering with the river's navigational channel. The approach spans were built using scaffolding for the main box and, for the precast panels and side cantilevers, a wing traveller was used, supported from the already complete section.

Arup and CFC developed the erection engineering and geometry control during construction, with the design refined using state-of-the-art structural analysis tools, such as explicit time-dependent curves and step-by-step non-linear iterative analysis. Two independent models – one developed by each consultant on the design team – with more than 450 construction stages were used and updated with real data as the cantilever construction developed. Deck deflections up to 700mm for a single stage were predicted and observed at the latest cantilever stages.

Due to the single plane of cables located in the central median, transversal post-tensioning – in addition to the main cables and conventional longitudinal post-tensioning – was part of the chosen solution developed at the detailed design stage. This required a combination of global and local modelling and analysis, using 3D finite element non-linear models with time-dependent properties and non-linear properties. To accelerate the final stages of construction, an analysis tool overlapping the final stressing of the cables simultaneously with the placing of the superimposed dead load was developed. This enabled the cable forces to be updated in real time, substantially reducing construction time.



10.

11.

11: The bridge opened in January 2020, and has improved congestion and national and international connectivity

Constructing the bridge required significant temporary works, including two temporary piers and a temporary artificial peninsula formed to facilitate construction of the main central pier. Reviewing the temporary works design was a critical part of Arup's role coordinating health and safety in the design process. Given the nature of the construction method, with its balanced cantilever and the complexity of each construction cycle – with post-tensioning in both directions – a fully integrated construction-design team was used on the project. In addition to the conventional design site representatives, senior bridge designers from both Arup and CFC were permanently based on site during the final two years of construction, providing ad-hoc specialist services and dynamic feedback to the construction team during the cantilever construction.

Landmark bridge

The Rose Fitzgerald Kennedy Bridge is a critical part of the N25 New Ross bypass, which provides improved regional, national and international connectivity. Not only easing congestion for the residents of New Ross, the bypass links Cork and Waterford to Rosslare Europort, with its ferry connections to the UK and continental Europe. It also links the N25 with the N30 New Ross to Enniscorthy route, two of Ireland's key commercial and tourist routes.

The bridge represents a state-of-the-art achievement in terms of extradosed bridges. At 230m, the two main spans are the longest of this type in the world for a full concrete deck. The bridge meets strict requirements in terms of aesthetics, having a distinctive profile owing to its three low towers of different heights and its sloped profile and slender deck, meaning it blends in with the local surroundings.

Authors

Mike Evans was the Project Director. He is Arup's Europe region highways business leader and a director in the Dublin office.

Cian Long was part of the design team based on site during construction. He is a senior engineer in the Dublin office.

Alfonso Ramirez was part of the design team based on site during construction. He is a project engineer in the Dublin office.

Marcos Sanchez led the bridge design. He is Arup's Europe region bridge and civil structures leader and a director in the Dublin office.

Project credits

Client New Ross Joint Venture delivering to Transport Infrastructure Ireland
Bridge sub-consultants Carlos Fernandez Casado SL
Contractor BAM Civil Ltd. and Dragados Ireland Ltd.
Third party checker Eptisa and SYM
Road safety auditor PMCE
Ecologist Flynn Furney Environmental Consultants
Bridge, civil and highways engineering, environmental consulting, geotechnics, hydrodynamic modelling, project supervisor design process services, site supervision, and sustainable infrastructure design Arup:
Yalda Acar, Martin Allen, Ozgur Alper, Ian Anderson, Greg Balding, Antonio Barrias, Kevin Barry, Conor Beades, Jenna Beckett, Roland Bourke, Chris Bradish, Diarmuid Brennan, Cian Buckley, Marcin Bulkowski, Finian Burke, Gokhan Cakan, Alan Callan, Aidan Cleary, Thomas Connell, Ole Daetz, Jade Daloyoc, Heinz Engela, Mike Evans, Alan Finch, Marie Fleming, Sean Fox, Annmarie Gallagher, Rachael Gannon, Heather Gibbons, Claudio Grandi, Georgia Hall, Gerard Hall, Mariusz Heczko, David Hetherington, Lukasz Hetmanski, Pernille Hornshøj, Albin Ingmarsson, Michal Jajesnica, Tomasz Jaworski, Jen Kennedy, Jennifer Lee, Cian Long, Esther Madden, Gillian Madden, Kieran Malone, Kinga Marecik, Luis Matamala, Nathan Maxwell, Maeve McElligott, Alba Menendez, Ed Mullen, Rafal Nowak, John O'Donovan, Pawel Ogonowski, Aoife O'Riordan, Alan Pettit, Tomasz Pietruniewicz, Alessandro Rama, Alfonso Ramirez Marchena, Ignacio Rivero, Zacarias Rosillo, Diego Rubio, Rinalds Rublis, Jose Ruiz, Marcos Sanchez, Claudia Sanroman, Anna Skwarek, Sergey Tatuyko, Benoit Thomyre, Janice Topley, Daniel Verdugo, Frederik Vind Jensen, David Wallace, Daniel Walsh, Lukasz Wozniczka, Greg Zabicki, Pablo Zalvide Hernanz.

Image credits

1, 2, 4–8, 10: Arup
3, 9: Ian Cahill/insta_mavic
11: Royston Palmer

1.

On the right track

Leading the design to transform an essential part of the UK's railway infrastructure

Authors Luke Cooper, Nigel Fletcher, Michael Nops, Dan Raynor, Peter Richardson, Tarek Sadek, Austin Smith and Gareth Thompson

Electrification of the Great Western Railway mainline between London and Cardiff has been a major element of The Greater West (TGW) enhancement programme and the largest rail electrification project undertaken in the UK since the 1980s. The £3 billion programme, substantially completed in December 2019, has transformed the Great Western Railway, introducing electric trains and enabling a completely new timetable. The result is shorter journey times and more frequent services, with an extra 15,000 seats each weekday between Cardiff and London. It has also brought environmental benefits, reducing noise pollution and improving air quality. The Hitachi Intercity Express trains used on the route are 18% more energy efficient than diesel class trains, and it is estimated that the electrification of the Great Western Railway network will result in the reduction of over 40,000 tonnes of CO_2 equivalent emissions each year.

Arup had been centrally involved in TGW since undertaking feasibility studies directly for Network Rail in 2011. This work included route clearance studies and optioneering of electrification solutions in the tunnels. Arup was appointed in 2014 as the lead designer for sections 8 and 9, extending from Patchway on the outskirts of Bristol, through Newport to Cardiff. These sections covered 57km of multiple track through complex areas of the route, taking in the major stations at Newport and Cardiff, and the 7km Severn Tunnel that connects England and Wales.

1: The Greater West enhancement programme has transformed the Great Western Railway

The Bristol to Cardiff electrification work was delivered through design and build (D&B) contractor partners ABC Electrification (a joint venture comprising Alstom, Babcock and Costain), and subsequently Balfour Beatty, with AmcoGiffen delivering the tunnels contracts. Arup worked as the lead designer alongside design partners Tata Special Projects (which produced most of the standard 'open route' designs), and was supported by sub-consultants Furrer+Frey (F+F), SNC Lavalin, WSP, Opus and COWI.

Lead designer

As lead designer for sections 8 and 9, Arup led the multidisciplinary design of the overall electrification works. The scope of work included the overhead line equipment (OLE) and associated electrification components, OLE support structures and foundations, tunnels, bridgeworks, and the coordination and integration of all lineside infrastructure.

Arup mobilised a multidisciplinary team from its rail business, with support drawn from all sectors, covering all technical disciplines and internal project management services. Over 450 Arup staff across 21 offices provided input on the project.

Project Management Office

To enable delivery of the works, Arup collaborated with Network Rail and ABC to establish a Project Management Office (PMO) to provide leadership and management of the whole pre-construction process, including surveys, design and assurance. An integrated programme of work was established to allow construction to proceed in parallel with finalising the design; this was essential in meeting the programme deadlines. To assist ABC, members of the Arup team were seconded into the PMO to form a co-located project team in Newport.

One of the main challenges was working within a live railway environment, with the railway remaining operational throughout the project. Most of the works were done in heavily congested railway corridors with existing Victorian-era structures and a multitude of lineside equipment and buried services, with little information on their location or asset condition. The PMO model allowed integrated planning of access arrangements for surveys, design and assurance, and subsequent construction activities within track possessions (when the railway was closed to trains for a period of time, either a few hours or up to several days). Major blockades of up to six weeks were arranged to enable large packages of site works to be completed efficiently.

Another primary PMO function was the management of interfaces with other Network Rail projects and integration of the design with works being delivered by others, including high-voltage (HV) power and distribution, signalling and route clearance works.

2.

Arup worked closely with ABC and Network Rail to establish a project-wide assurance strategy, allowing progressive design submissions and acceptance to run in parallel with site activities. This enabled the PMO to manage the combined design and construction programme. Assurance functions and systems engineering activities included:

- technical assurance to follow Network Rail procedures, enabling acceptance of integrated designs by the relevant Network Rail disciplines and asset owners;
- requirements management, including validation and verification processes against the contract requirements;
- safety management, managing inputs for a project-wide hazard register to assess risks and provide system safety evidence in support of design submissions; and
- interface management, identifying all project interfaces and stakeholders and setting up interface controls to ensure technical coordination of designs and implementation of works.

BIM and digital tools

Arup led the BIM strategy for the Bristol to Cardiff route section, working in collaboration with Network Rail and ABC. This involved creating innovative and powerful data collection and visualisation tools, which greatly reduced the number of surveys and site visits required and helped to streamline the design process. By using 3D, web and mobile technology, the project team was able to capture a large array of data quickly and easily and share it via a common data environment.

The digital tools comprised three elements:

- a relational database linking and integrating previously separate digital platforms, existing data sets and ever-expanding volumes of site data;
- an app that captured real-time geotechnical investigation trial pit data, which fed directly into the database and interfaced with design software; and
- a rail-specific web viewer that enabled multiple stakeholders to view, access and interrogate various data sets from any device and location.

These processes and tools were developed specifically for sections 8 and 9 of the route, and were then adopted by Network Rail on further sections of TGW.

3.

2: Arup was lead designer on TGW sections stretching from the outskirts of Bristol to Cardiff

3: Through the use of web, 3D and mobile technology, the large project team could capture and share a wide range of data in real time

4.

5.

All parties with access to the web viewer benefited from being able to see map data, site photos, 2D and 3D geometry, 360° imagery – including a railway version of 'streetview' – point clouds, trial pits in real time, pile foundation installation and as-built survey data.

A specific function of the app on hand-held devices was used to validate OLE mast/foundation positions through the use of trial pits on site. The tool allowed real-time visibility of trial pit information to be shared between the site team and designers. Not only could foundation locations be validated easily, but any iteration needed to adjust design positions to avoid buried services could be done efficiently. The app was also developed to capture as-built data, automatically feeding this into the database, with visibility through the web viewer.

These digital tools generated significant, quantifiable benefits in terms of improved safety and carbon reductions. It was estimated that over 6,000 hours were saved by removing onsite paper-based trial pit records and associated datasheet processes and resources. During the design phase, the web viewer is estimated to have saved 13,000 work hours and resulted in a 70% reduction in design team site visits.

The success of these innovative tools has been recognised through industry awards, including the 2017 Constructing Excellence (National) Digital Construction Award.

OLE foundations

The design and installation of the foundations for the OLE were significant elements of the overall scheme – 13,000 foundations were required along the full length of the Bristol to Cardiff section. Significant challenges faced and overcome included:

- lack of surveys – including topographical, ground investigations and buried services data;
- limited access available to undertake surveys;
- varying ground conditions; and
- constraints on OLE mast/ foundation locations.

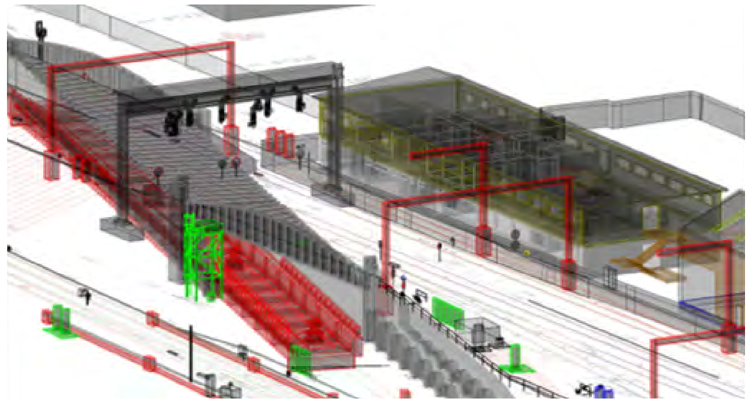
Arup arranged site investigations to allow ground models to be developed and to identify the main ground hazards. These investigations included trial pits, boreholes and dynamic sampling methods, with additional investigations carried out in areas of greater ground risk or uncertainty. This work also informed

6.

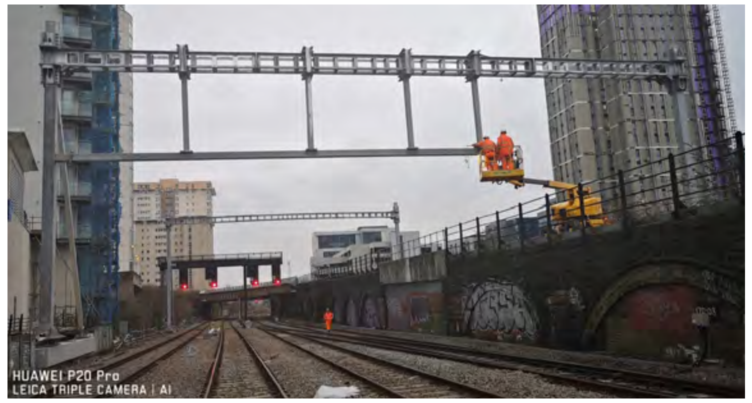
4: Driven steel circular hollow section piles were the preferred type of OLE foundation

5: In areas where there were significant headroom constraints, such as beneath station canopies, mini-pile foundations were used

6: 3D imagery was used to obtain statutory consents from planning and heritage authorities



7.



8.

the investigations necessary to confirm the form and condition of the existing structural assets, many of which date back to their original construction in the mid-19th century, and to assess the potential impacts of the OLE system and its foundations on these assets.

The preferred OLE foundation comprised driven steel circular hollow section (CHS) piles, favoured due to their relatively high installation productivity rates and low relative cost. Groups of mini-piles were also adopted within areas of significant headroom constraints, for example beneath the station canopies in Cardiff and Newport stations.

Difficulties with the installation of foundations to design depths was a critical programme and cost risk for the scheme. Understanding the ground conditions and the limitations of available construction plant in installing different types of foundations within these differing ground conditions was an important consideration from the early stages.

Collaboration with Network Rail and piling subcontractors and designers across other sections of TGW allowed the teams to develop a better collective understanding of the limitations and capabilities of the construction plant. Based on these findings, Arup developed an innovative small diameter bored piled option that could be readily installed using available plant. This significantly reduced the number of abortive foundation installations in areas of stronger shallow rock, improving productivity, reducing costs and helping to protect the wider programme of delivery.

There were a small number of foundations that did not achieve the defined design depths due to refusal on hard strata. The Arup team undertook back-analyses of these foundations based on the specified piling records and ground conditions encountered. In many instances, this allowed the adequacy of the installed foundations to be demonstrated, avoiding the need for expensive remedial works.

A bespoke automated software tool integrated with geotechnical software design tools ALP and PIGLET was developed during the project, which enabled improved productivity by allowing the mass production of location-specific foundation designs. As the surveys, design and construction activities progressed together, all data was held in a ‘single source of truth’ schedule, combining the OLE and foundation designs in a single model.

OLE design

The OLE equipment range implemented on the Great Western mainline was Series 1, developed by F+F for national electrification projects on routes above 110mph. The benefits of using Series 1 included a reduction in the standard OLE components, which minimised installation times and track possessions, and reduced maintenance requirements.

Arup worked with F+F to develop OLE solutions for the complex sections of the Bristol to Cardiff route, allocating the Series 1 design range and using inputs on HV power feeding and sectioning arrangements provided by Network Rail. The OLE design process involved producing preliminary layouts to enable foundation selection, followed by detailed layout plans and design, material schedules, and clearance assessments for structures and signals. The creation of the initial concept design allowed mobilisation of the ground investigations for foundation works at an early stage, which was critical in meeting the overall programme timescale. The detailed design included traction bonding design and overall coordination with lineside civils infrastructure and earthing and bonding designs as part of the electrification system.

9.

7: 3D modelling was used to integrate the design with station infrastructure and for safety assessments

8: Bespoke OLE structures and foundations were required on the congested station approaches

9: A rigid overhead conductor rail system was installed in TGW tunnels

Major stations

The major stations at Cardiff Central and Newport presented unique challenges in incorporating electrification systems that would have minimal impact on the station infrastructure and railway operations.

Arup worked closely with Network Rail, station operators and local authorities to develop bespoke OLE structure solutions. These were integrated within existing platforms and canopies, minimising the impact on heritage structures and on station usage for both train operators and passengers. Where possible, OLE structures were placed away from areas of passenger flow and situated to avoid conflict with signal sight lines. Extensive consultations were necessary to obtain statutory consents from planning and heritage authorities, involving the use of 3D imagery to demonstrate the mitigation measures introduced to reduce visual impact.

10.

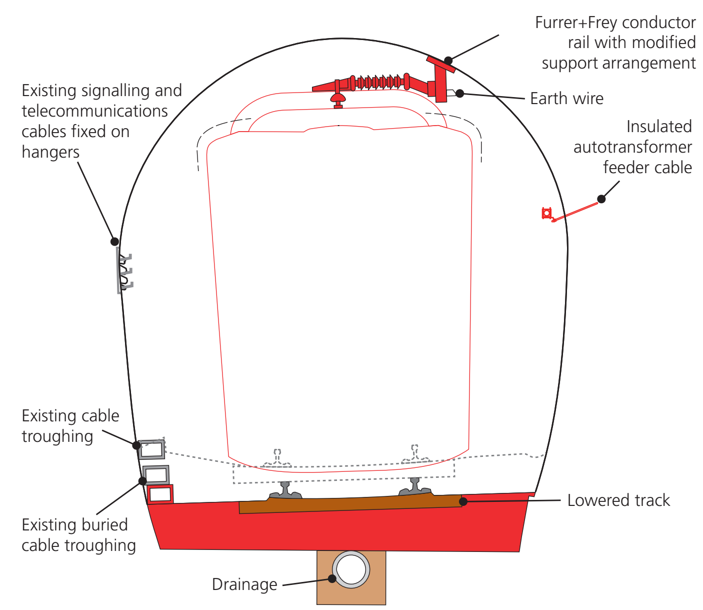
Risk assessments were undertaken to ensure all station operations and maintenance activities could be done safely and that minimum clearances to any live electrical equipment were maintained. An example of this approach was the autotransformer feeder (ATF) cable and routing design. Following optioneering studies, Arup developed solutions using insulated ATF cables, mainly routed behind the station buildings to avoid the platform areas.

OLE designs on the approaches to both major stations were highly complex due to the narrow, congested railway corridors, including frequently opposing constraints presented by the proximity of over and under bridges, railway junctions and retaining structures. These necessitated bespoke solutions, not just for the OLE itself, but for support structures and associated lineside equipment.

Tunnels electrification

Electrification of TGW mainline tunnels presented two main challenges: integrating electrification design within the constraints of the existing Victorian-era tunnels and implementing the works within limited railway possessions. Arup undertook feasibility studies for Network Rail to establish the preferred design option for each of the six tunnels between Bristol and Cardiff and one other tunnel at Chipping Sodbury to the east of Bristol (which was subsequently added to the Arup scope). Each tunnel required a phased approach to undertake surveys, design and construction works, all in close collaboration with Network Rail and AmcoGiffen as the D&B contractor for the tunnel works.

Innovative electrification designs were introduced through close liaison with the OLE design partner F+F. A rigid overhead conductor rail system (ROCS) developed by F+F was typically used, to provide optimum solutions within the limited space available. The ROCS consists of an aluminium conductor rail which holds the contact wire in place, eliminating the need for tensioning equipment and thereby improving safety and reliability. In the 4km-long Chipping Sodbury Tunnel, the design was the first application in



11.

10: In the Patchway tunnels, track had to be lowered by as much as 400mm

11: The Patchway tunnels required a modified ROCS to suit the tunnel profiles and to minimise track lowers

12.

12: The Bridge Street overbridge was replaced in a single lift operation

13: It is estimated that the electrification of the Great Western Railway will result in the reduction of over 40,000 tonnes of CO_2 equivalent emissions annually

the UK of a conductor rail OLE system on a 125mph mainline railway.

The Patchway tunnels north of Bristol presented a unique set of challenges. These twin, single-bore tunnels have particularly tight spatial constraints. The tracks needed to be lowered by up to 400mm to provide the required space for the OLE, with temporary excavations in excess of 1m deep needed in places to replace the track, formation and tunnel drainage. Rock bolts (4.5m long at 2.5m centres) were installed where required to provide lateral restraint to the base of the tunnel walls, in advance of the autumn 2016 six-week blockade for the main track lowering works.

At approximately 7km in length, the Severn Tunnel is the longest rail tunnel in mainland UK. With the added complexity of crossing beneath the River Severn estuary, water management measures were necessary to minimise the effects of water ingress on the OLE system. The electrification equipment was installed in phases, with the main ATF cables and ROCS system installed during the 2016 blockade. This allowed subsequent monitoring, inspections and testing to take place to assess the effects of the adverse environmental conditions within the tunnel, enabling additional mitigation and protection measures to be applied prior to final commissioning.

For the design of the structural fixings into the tunnel lining, intrusive investigations were made in the early design stages to assess the condition and integrity of the tunnel linings and to undertake trial fixings and pull-out tests. Standard designs, using proprietary bolts and chemical grout products, were subsequently developed to suit a range of load cases and structural conditions likely to be encountered. Fixings were then installed using innovative drilling rigs specially developed by AmcoGiffen for TGW tunnels. These enabled rapid, safe installation within the tight spatial and time constraints.

Bridges and civil structures

Along the route, major clearance works were required including bridge renewals. Most significantly, Arup undertook the full design of the replacement of the 39m-span Bridge Street overbridge in Newport. The 120-year-old bridge had insufficient vertical clearance for the electrification works. It was removed in a single lift operation and replaced with a new single span weathering steel-concrete composite road bridge that met the clearance requirements. The design of the new superstructure consisted of prefabricated steelwork and precast concrete deck and parapet elements that allowed works to take place during short possessions to minimise rail disruption. The original substructure was assessed and retained with some modifications to improve stability. The increased load capacity of the superstructure allowed the removal of the previous weight restrictions for traffic on the bridge and the footpath widths were increased to improve pedestrian access to the city.

Various bridges and viaducts required modifications to accommodate the bespoke OLE support structures. These included portal gantries attached to the steelwork of the Usk Viaduct and six-track portal gantries between Cardiff Central and Cardiff Queen Street, spanning the split-level tracks of the South Wales mainline and the Valley Lines.

Lessons learned

The first electric train services between London and Cardiff commenced on 5 January 2020. This was the culmination of many years of collaborative effort within a challenging programme across numerous contracts. Arup helped to transform this vital UK rail corridor into an environmentally sustainable, electrified railway.

Innovation was at the heart of Arup's work – the team developed bespoke software and visualisation tools to integrate site survey information with design models, as well as developing pioneering OLE foundation design and electrification solutions.

Many lessons have already been learned from TGW, not only for Arup but for the entire rail industry. The firm has contributed to developing strategies for future electrification schemes through industry-wide bodies including the Railway Industry Association. Arup has since applied its learnings from TGW on major rail projects elsewhere, including HS2 and the Transpennine Route Upgrade.

13.

Authors

Luke Cooper led the BIM implementation on the project. He is a senior analyst in the Cardiff office.

Nigel Fletcher led the original feasibility studies for Network Rail and the initial Lead Design Team as Contractor's Engineering Manager. He subsequently led the Assurance Team for ABC Ltd and was the Project Manager for the tunnels contracts. He is an Associate Director in the Bristol office.

Michael Nops was the Project Manager for the main OLE contracts, and part of the PMO. He is an Associate Director in the London office.

Dan Raynor led the geotechnical design of the OLE foundations. He is an Associate Director in the Cardiff office.

Peter Richardson was the Contractor's Responsible Engineer for Bridge Street overbridge reconstruction, the ATF fixings in the Severn Tunnel and many of the civil structures adjacent to Newport and Cardiff Stations. He is a Senior Engineer in the Cardiff office.

Tarek Sadek led the Patchway Tunnels stability analysis and geotechnical engineering to enable the track lowering works. He is an Associate in the Bristol office.

Austin Smith was the Programme Director. He is a Director and is the Bristol office leader.

Gareth Thompson was the lead Contractor's Responsible Engineer for OLE design. He is a senior engineer and technical lead for the OLE team, based in the Manchester office.

Project credits

Ultimate client Network Rail
Direct clients/contractors ABC Electrification Ltd (JV with Alstom, Babcock and Costain), Balfour Beatty and AmcoGiffen
BIM, bridges, civil, digital services, electrical engineering, environmental consulting, geotechnical engineering, highway design, programme and project management, railways, structural engineering and transport planning Arup:
Obie Achigbu, George Acuna, Sara Ali, Pete Allott, Alina Alvarez, Allen Amin, Josh Archer, Dave Ashurst, Sylvester Atiba-Davies, Clive Aubrey, Victoria Aviomoh, Hamza Baayu, Jacek Bacinski, Grace Baird, Charlie Baldwin, Sam Baldwin, Samila Bandara, Raphaelle Barbier Saint Hilaire, Chris Barker, Patrick Barry, Ben Baty, Stephen Baxter, Rachel Beal, Anne Bearne, Jon Beech, Darragh Beirne, Lucy Bell, Claire Bennett, Nicholas Berg, Andrea Bertoneri, Robert Best, Ellis Blackmore, James Blyth, Dominic Blythe, Ed Boss, Mark Brayshaw, Chris Brieger, Alex Briggs, Mike Brizell, Matthew Brown, Tansin Brown, Lukasz Bugajski, Mollie Bullock, Steff Bullock, Amanda Bulmer-Thresh, Mike Burke, Peter Burns, Amanda Burrows, Andy Button, Flavia Cappelletti, Juan Carlos Ascanio, Neil Carstairs, Agnieszka Cepok, Laura Chatwin, Alpesh Chauhan, Mei Cheong, Martin Chibhebhe, Les Church, Lewis Cleverley, Barrie Coles, Paul Cone, James Connell, Luke Cooper, Mark Cooper, Jack Copner, Matt Crawford, Matt Cresswell, Jamie Crispin, Sebastien Crompton-Roberts, Wilma Cruz, Ross Cullen, Joe Daly, Anna David, Ceri-Ann David, Rob Davies, William Davies, Tomas Davis, Lee Davis, Mark De Melo, Alan Dean, Rachael De'ath, John Dell, Rory Deuchar, Brian Devlin, Alexia Dimitriou, Tim Dixon, Peter Dodd, Shaun Doherty, Kieran Dolan, Mark Douglas, Georgie Durell, Amit Dutta, Mark Easton, Amy Edmonds, James Edwards, Rowen Ekermawi, Iolo Ellis, Sue Elias, Qusay Elshawa, Andrew Emmerson, Chris Evans, Ioan Evans, Jayne Evans, Kieran Fargher, Mike Farrer, Lindsey Fletcher, Nigel Fletcher, Jonathan Fowles, Matthew Fox, Will Francis, Matt Fry, Alex Fullerton, Catherine Gainey, Ana Gallego, James Gibbons, Rob Giles, Elena Gogou, Rob Gordon, Martin Gormley, Felicity Graves, Josh Green, David Gregory, Daniel Griffith, Stuart Haden, Zoe Haigh, Dave Hamblett, Colin Hanford, Jim Harbord, Alison Harper, Phil Harrison, Shaun Hartley, Chris Harwood, Mike Haughton, David Hay, Dave Heard, Welayat Hosany, Daniel Howse, Will Hughes, Alastair Hume, Dave Hunt, James Hunt, Richard Hunt, Andrew Hurst, Simon Hurst, Salma Hussein, Andy Illingworth, David Ingram, Scott Ingram, Bob Irvine, Val Ismaili, Chris Jackson, Hywel James, David Jarvis, Tomasz Jaworski, Jaroslaw Jendrzejczak-Jendrzejewski, Erqin Ji, Sally John, Darren Jones, Andrew Jones, Chris Jones, Mathew Jones, Neil Jones, Rosheena Jugdhurry, Chris Justice, Dan Kang, Zach Kanter, Rahul Karunakaran, Karen Kennedy, Jack Kerr, June Khine, Andrzej Kocmierowski, Maciej Kolodziejski, Alexandra Koutsouki, Kamil Kroplewski, Irek Kryczka, Michal Kurzewski, Nameeta Lal, Joe Landers, Phil Landrey, Jordan Laraway, Robin Larcombe, Witold Laszcz, Jasmine Lau, Simon Lawrence, Jakub Lech, Mariusz Leszczynski, Charlie Levett, Oliver Lewis, Bogumil Lipiecki, Philippa Long, Emiliano Lopez, Luis Lozano, Sinéad Lynch, David Lynesmith, Evan Ma, Ian Mach, Jack Macnaghten, Panagiotis Manis, John Manning, Sarah Maplesden-Jenkins, Daryl Marshall, Charlie Martin, Shannon Martin, Zoe Masterson, Giulia Matteoni, Sophie May, Suzanne McColgan, Colin McCreath, Rory McEwan, Joseph McGenn, Kelly McKay, David McShane, Victoria Megraw, Maurizio Mele, Nette Mijares, Laura Millar, Nicola Millard, Saeed Mojabi, Philip Morgan, Phil Morley, Annabel Morris, Glyn Morris, Sam Moss, Andrew Murnane, Blake Murnane, Jonny Murrells, Tom Mynors, David Nash, James Nicholls, Michael Nops, Chris Norman, Stine Norskov, Paul Nottage, Caroline Nurse, Clare O'Connell, James O'Dwyer, Henry O'Grady, Nonso Okoye, Kwesi Okutu, Ed Olivier, Marcel Onwuka, Michael Orr, Anthony O'Shea, David Overall, Chris Owen, James Park, David Parks, Tom Partington, Richard Patten, Jonathan Payne, Jamie Pearce, Sean Perryman, Anthony Peters, Aled Phillips, Gareth Pierce, Anton Pillai, Miguel Pinto-Ward, Chris Pope, Daniel Potts, Liam Power, Annie Price, Caitlin Price, Christopher Price, Natalie Price, Linda Pring, Declan Prior, Jacek Przysiezny, Maria Qabaha, Mario Querol, Sara Quintana, Antonio Raya, Dan Raynor, Paul Richards, Tara Richards, Peter Richardson, Jonathan Ridley, John Riley, Gill Ritchie, Colin Roberts, Richard Robertshaw, Duncan Robertson, Elliott Robinson, Joanna Rothwell, Tarek Sadek, Paddy Samengo-Turner, Luqman Samiruddin, Aaron Sammutt, Richard Sharp, Keelan Shelton, Dmitry Sidorenko, Mark Skinner, Tom Skinner, Matthew Skuse, Ian Smiley, Austin Smith, Daniel Smith, Joel Smith, Matt Smith, Matthew Snell, Rob Snell, Sam Soltesz, Katie Southway, Andrzej Stanulewicz, Tomasz Stawiarz, Gillian Steele, Tony Stimpson, Nikki Stockbridge, Darren Styles, Xiying Sun, Mohan Sundharam, Jakub Szkaradzinski, Davyd Tamrazov, Ji-Jian Tang, Lucy Taylor, Lee Taylor, Aodhan Teague, Anna Thiele, Toria Thomas, Gareth Thompson, Tim Thorne, Stuart Tillett, Dan Timmins, Philip Todd, James Tomnie, Andrew Tryhorn, Will Turton, Catherine Tyldsley, Mike Tyrrell, Jaunius Urbonas, Ben Urry, Rob Varley, Marios Venieris, Ian Walker, Louise Walley, Kirstin Walling, Alex Walton, Jonathan Ward, Mick Ward, Tom Watkinson, Chris Webb, Joanna Wei, Lisa West, Simon Westwood, Simon Wheat, Barry Whitehead, Barbara Wielgo, Dan Wilcox, Tim Wilkinson, Sam Wilks, Keith Williams, Nick Williams, Sion Williams, Mark Wilmot, Emily Wilson, Ivan Wong, Alastair Woodland, Marie Wright, Dunshun Yang, David Zhao, Ying Zhou, Susanne Zocher, Lutalo Zuberi.

Image credits

1: Gareth Willey/Shutterstock
2–8, 10, 12: Arup
9, 13: Network Rail
11: Arup/ICE

1. Raffles City Chongqing, Chongqing, China: CapitaLand Ltd; 2. Central Interceptor Tunnel, Auckland, New Zealand: Arup; 3. K11 ATELIER King's Road, Hong Kong: Marcel Lam Photography; 4. Long-Baseline Neutrino Facility, South Dakota, USA: Matthew Kapust/ SURF; 5. Jengu handwashing unit, Global: West Lea School; 6. Ken Rosewall Arena, Sydney, Australia: Martin Mischkulnig; 7. Rose Fitzgerald Kennedy Bridge, Kilkenny and Wexford, Ireland: Ian Cahill/insta_mavic; 8. Great Western electrification, UK: Network Rail.

Front cover image: Raffles City Chongqing, Chongqing, China: CY Tang.

The Arup Journal
Vol.56 No.1 (1/2021)
Editor: Macdara Ferris
Designer: Wardour
Email: arup.journal@arup.com

Published by Arup
13 Fitzroy Street
London W1T 4BQ, UK.
Tel: +44 (0)20 7636 1531

Printed by Geoff Neal Group
Produced on FSC® paper
and printed with vegetable-
based inks.