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Realising the 'Pearl of the Orient'

Shaping the stadium at the centre of Kai Tak Sports Park – a vibrant symbol of civic pride which resonates with Hong Kong's reputation as the 'Pearl of the Orient'

Authors Henry Chan, Vincent Cheng, Clement Ho, Anny Ip, Alvin Lam, Ben Lam, Bob Lau, Wei Lin, Gordon Ng, Calvin Siu, Nina Yiu

It is not often the opportunity arises to create an entirely new district in a densely packed city like Hong Kong. But that is what has been done on the shores of Kowloon Bay over the past two decades, with Arup helping to transform the 320ha site of the iconic Kai Tak Airport. Kai Tak Sports Park – Hong Kong's new hub for sports, entertainment and community events – is part of this transformative redevelopment of the airport into a next-generation urban district. The park represents the most important investment in sports infrastructure by the Hong Kong Special Administrative Region Government (HKSAR) in recent decades. It is also a key part of the government's long-term strategy to promote sports development in Hong Kong and to develop a 'mega event economy' across sports and entertainment programmes.

Arup has been involved with the redevelopment of the airport site since the late 1990s. The firm's work in the wider district includes the planning and design of the district seawater-cooling system – one of the world's largest such systems (a key initiative under Hong Kong's Climate Action Plan 2050 that saves nearly 100,000 tonnes of CO_2 emissions a year). Arup's work also includes road and rail links that seamlessly connect Kai Tak to the rest of the city, reducing congestion and travel time, and the design of a diverse portfolio of public, private and commercial buildings across the Kai Tak district.

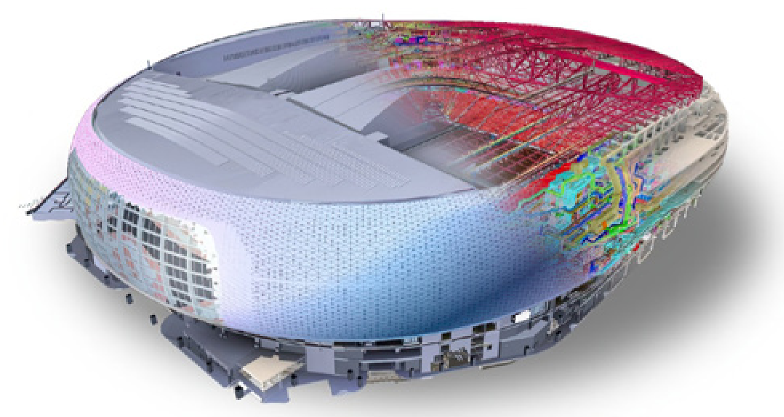
Most recently, the firm was part of the Design-Build-Operate consortium – led by the Culture, Sports and Tourism Bureau with Kai Tak Sports Park Limited as the contracted party – playing a pivotal role in the development of the 28ha sports park. Arup worked with Populous Limited (design architect), Simon Kwan & Associates (executive architect), ADI Limited (landscape architect), Hip Hing Engineering (design and build contractor) and Legends Global (operator) on the park, which incorporates three major sporting venues – Kai Tak Stadium, Kai Tak Arena and Kai Tak Youth Sports Ground – and includes 70,000m² of retail, dining and leisure mall facilities.

1: The stadium is located at the intersection of Shing Fung Road and the below-ground Central Kowloon bypass

2: Integrated openBIM was used for the modelling and coordination of both the roof and façade structure of the stadium

Kai Tak Stadium

The 50,000-seat Kai Tak Stadium is now an iconic landmark on Hong Kong's Victoria Harbour. The stadium, set in the heart of this dynamic sports complex, provides a world-class spectator experience. The venue's acoustically sealed retractable roof and flexible pitch surface enable it to host a variety of sports and entertainment events, regardless of weather conditions. Arup's engineering services strongly contributed to several



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Kai Tak Arena

The 10,000-capacity Kai Tak Arena is a versatile indoor venue designed to host a wide variety of sports and entertainment programmes. Adjacent to the Arena are three retail mall facilities, home to a 40-lane bowling alley and diversified sports brands.

The 80m x 100m main arena features a long-span steel truss roof and can host a wide variety of sports, including badminton, basketball, gymnastics, tennis, table tennis and volleyball. Its column-free design ensures unobstructed views from every vantage point and, with up to 80% of seating retractable or removable, the venue can be easily transformed for different events, from large-scale sports tournaments to community gatherings.

The roof steel structure is engineered to integrate seamlessly with the building services. It is also optimised for rigging loads, accommodating equipment such as speakers, lights, microphones and LED screens for various stage set-ups. A trafficable walking grid covering the whole playing area was introduced to ensure that the transformation from various sports and entertainment modes can be carried out safely.

Designing the building services to meet the specific needs of various sports while ensuring optimal air circulation and comfort for athletes and spectators alike, regardless of the event, presented a significant challenge. For example, stringent air velocity requirements are required for badminton. To address this, computational fluid dynamic analysis was conducted to assist the strategic locations for air inlets and outlets, to ensure precise control of mechanical flow speed and direction which meets international badminton standards.

Arup's sports lighting design adhered to rigorous international standards, ensuring the specific requirements of each sport were met. A key focus was placed on player comfort, utilising a glare-free design and high uniformity to enhance visibility. The system is also 4K broadcast-ready, meeting the high-definition standards required for live media. With integrated scene programming and adjustable lighting levels, operators can easily transition between different event profiles through customised luminaire grouping.

Kai Tak Youth Sports Ground

The 5,000-seat Kai Tak Youth Sports Ground is primarily used by the local community and for warm-ups by competitors during major sporting events. The central section of the venue's grandstand includes a series of transfer trusses to support the upper floors, spanning over 40m. This design transfers the load onto the large-diameter bored piles positioned either side of the Kai Tak Tunnel, a vital east–west artery in Kowloon that runs underneath the venue.

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3: The Kai Tak Arena's column-free design ensures unobstructed views and up to 80% of seating is retractable or removable, allowing the venue to be transformed for different events

4: The 5,000-seat Kai Tak Youth Sports Ground is primarily used by the local community and for warm-ups by competitors during major sporting events

5: The four primary trusses – weighing in at 6,200 tonnes – were lifted up to their final position over a 10-hour period using four temporary jacking towers

6: The roof steelwork was fabricated in the western Pearl River Delta and shipped to the site by barge in sections

of the building's unique features. The structural team was challenged to produce an economically efficient roof design while catering for the retractable roof and the requirement to have good sound insulation. The stadium cooling system provides a comfortable venue at pitch level and right around the stadium bowl, with the air duct system integrated into the modular construction of the bowl. The venue also includes a 30m-tall glazed wall that offers a spectacular view over Kowloon Bay towards Hong Kong Island. Arup's wide range of multidisciplinary services provided for the stadium included civil, structural, geotechnical and building services engineering, as well as traffic, fire, façade, acoustics, audio visual, lighting, advanced digital engineering, security, environmental and sustainability consulting.

Optimised foundation design

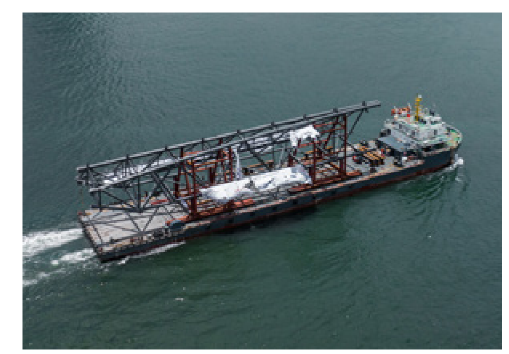
The foundations of Kai Tak Stadium utilise a combination of end-bearing, large-diameter reinforced-concrete bored piles up to 70m in length and friction-driven H piles approximately 40m long. Large-diameter bored piles were installed at the four cores supporting the main Eye-Trusses of the roof, while driven H piles were used for all grandstand portions.

Careful consideration of differential settlement between these pile types, negative skin friction evaluation, along with necessary structural layout modifications, ensured an optimal balance between rigid roof support and overall savings in construction time and cost.

Designing the iconic roof

The stadium's unique roof structure includes a fixed section above the seating area and a retractable section over the pitch. To achieve the elegant pearl appearance, which reflects Hong Kong's identity as the Pearl of the Orient, Arup moved away from the conventional exposed arch or dome systems for the design of the roof, as they would not achieve the aesthetic requirements or enable a soundproof concealed retractable roof design.

The firm developed a bespoke orthogonal Eye-Truss system shaped and stacked to create a clean and cohesive roof structure that married with the stadium architecture developed by Populous. The retractable roof system is acoustically sealed, and opens and closes



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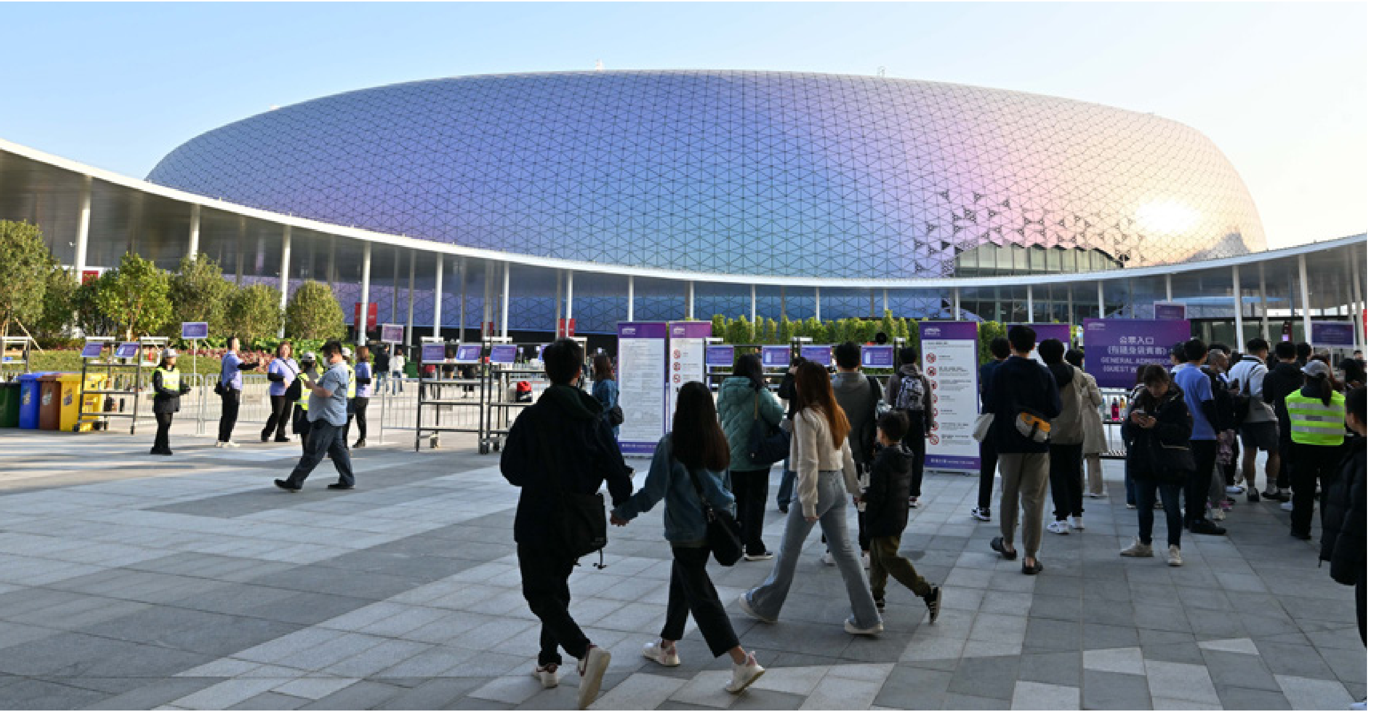

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7: 3D MassMotion simulations were used to understand spectator movement under various scenarios, taking into account the mobility speeds and capabilities of diverse groups

8: The venue includes a 30m-tall glazed wall that offers views out over Kowloon Bay towards Hong Kong Island

9: The stadium's air conditioning is powered by the Kai Tak district cooling system, which is significantly more efficient than traditional equivalents

silently to allow the seamless transition between open-air sporting events and fully enclosed concerts. It is one of the largest of its kind in the world and is supported by two pairs of orthogonal main trusses spanning from 150m to 180m.

Integrated openBIM was used for the modelling and coordination of both the roof and façade structure of the stadium. Arup generated the steelwork setting-out and design information from a parametrically driven digital model. This was further developed by the steelwork fabricator with the Tekla model containing all the fabrication details, including plates, brackets, nuts and bolts. The completed model was then shared and coordinated with various subcontractors through openBIM, allowing them to record their respective interfacing details in the LOD-400 model and providing a seamless approach to all parties.

The roof steelwork was fabricated in multiple facilities across the western Pearl River Delta and shipped in sections to the site by barge. The first piece of the main roof truss was delivered to site in September 2021. Weighing almost 300 tonnes, including its temporary supports, it measured 66m long x 15m tall. The truss was mounted on 12 self-propelled modular transporter (SPMT) units before shipping. These were used to unload the truss piece without heavy craneage by driving it directly from the barge via a steel link span to a temporary platform erected behind the sea wall (so as not to overload it). Once on land, the SPMT units drove the truss piece via a specially prepared right-of-way to a temporary parking area at the stadium next to the pitch. This was the first of a series of roof section shipments, the largest of which weighed over 1,100 tonnes, with some of the later sections also stored on the pitch. In total, there were 10 main truss segments for the fixed roof and eight segments for the retractable roof.

The barge delivery to the site allowed most steel fabrication works to be completed offsite, thereby promoting quality and avoiding large numbers of truck movements to and from the stadium. The roof sections were stitched together and then lifted as one in late May 2022. This operation saw the four primary trusses – weighing in at 6,200 tonnes – lifted up to their final position over a 10-hour period using four temporary jacking towers and a strand-jacking technique.

Safe execution of the works was of paramount importance, particularly as the lift took place during Hong Kong's typhoon season. A nine-day window of clear weather forecast was required before the lift could proceed. Arup played a vital role working with the main contractor Hip Hing in formulating the risk management plan and contingency measures prior to the lift to ensure everything would go smoothly. The firm also utilised its intimate knowledge of the roof steelwork design with the aid of BIM to advise on key issues related to truss connection fit-up.

Once the trusses were lifted into position, an intense period of work followed to connect them to their supports at roof level. This included welding, bolting and reinforced-concrete casting. All these works were completed within four days during the clear weather window and ensured that the structure would remain stable if the weather conditions deteriorated. Arup's resident site supervision team was deployed in shifts to cover this period and played an essential role in assuring the quality of the work.

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Once in place, the skeleton of the main stadium roof formed the principal loadbearing structure, supporting the fixed part of the roof and the retractable section.

Acoustically sealed retractable roof

Weighing nearly 4,800 tonnes, the two retractable panels of the roof operate on mechanisms similar to railway bogies with flangeless wheels. This allows the roof to open and close silently over approximately 30 minutes, enabling the atmosphere and functionality of the stadium to be changed completely. The acoustic design needed to take into account the fact that, when the roof is being closed, its large internal volume could cause excessive sound reverberation, which could compromise acoustic clarity and detract from the overall sound quality during concert performances. To mitigate this issue, the Arup team included a mix of noise-absorbing materials in the design, strategically placed to reduce sound reflections and enhance overall acoustic performance.

Given the proximity to residential areas – only 220m away – it was crucial that the roof effectively contains noise, especially during late-night events such as concerts. To this end, the retractable roof incorporates a number of different seals around the perimeter and utilises roof panels constructed from multiple layers of sheet materials (each measuring 148m by 45m and weighing around 2,400 tonnes in total) to damp low-frequency sounds. The multi-layer design, 800mm to 1,450mm thick,

Awards

- **HKIE Structural Excellence Award 2025** Grand Award – Hong Kong infrastructure and footbridges
- **Hong Kong Green Building Award 2025** Grand Award – New Buildings (Completed Projects – Institutional)
- **MIPIM Asia Awards 2025** Best Cultural, Sports and Education Project – Gold
- **buildingSMART openBIM Awards 2024** Winner (Design for Buildings)
- **Hong Kong openBIM/openGIS Award 2022** Grand Award (Project category)
- **Association of Consulting Engineers of Hong Kong (ACEHK) Annual Awards 2024** Overall Best Award
- **Hong Kong openBIM/openGIS Award 2024** Grand Award (Facilities Management / Asset Management category)
- **HKIE Legacy Awards** Grand Award (Infrastructure category)
- **HKIA Award of Hong Kong** Awardee (Civic & Communal Building)
- **HKIA Special Award** Awardee (Technology or Innovation Architecture)
- **MUSE Design Awards** Architectural Design – Stadium / Arena, Design of the Year and Platinum Winner

includes a sound insulation layer on top and a sound absorption layer on the bottom, made as light as possible to reduce the load on the structure.

Managing water drainage when the roof is closed posed a significant design challenge. The sharp edge of the roof, which offers a sleek visual profile when open, forms a large valley when closed. To address this, a series of gutters channel water from the valley to the back of the retractable roof, where it is then directed onto the fixed roof before entering the main drainage system. The entire roof incorporates a siphonic drainage system to maximise headroom while minimising pipe size and fall. This ensures efficient water drainage over long runs without compromising the stadium's structural integrity or aesthetics. By using smaller pipes and fewer vertical drops, the design maintains both the roof's aesthetic appeal and functionality, saving space and providing a seamless experience in any weather. The rainwater runoff is used for irrigation purposes within the sports park. Over 10% of the roof area is also equipped with photovoltaic panels, harnessing solar energy to power the facility.

The Pearl of the Orient façade

The stadium's shimmering façade, composed of approximately 27,000 triangular aluminium panels, captures the Pearl of the Orient theme of the venue. Each panel is coated with a Fluropon Kameleon Lightning Mist that changes into various pearlescent hues depending on the daylight intensity. An additional layer of Fluropon Clean with proprietary hydrophilic technology causes rainwater to spread across the panels, allowing dirt or pollution to be naturally washed away. The ventilation louvres were carefully concealed inside a multi-functional trench surrounding the roof.

In the evening, dynamic light shows transform the stadium into a dazzling spectacle set against Hong Kong's night sky. Arup's façade and lighting designers worked closely to realise this captivating effect. Thorough visual analyses were conducted to strategically position light fittings across the façade, tailor-made to enhance the stadium's grandeur, considering its height and scale, while reducing sky glow to minimise light pollution. After extensive testing of different wattages, the lighting team selected 2-watt lights, achieving an optimal balance between visibility from distances and energy efficiency. Fewer lights are positioned at the top of the façade to minimise upward lighting and sky glow, while denser lighting at the bottom improves visibility.

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10: A sophisticated computer analysis was used to verify that the vibration comfort of spectators met international performance-based criteria for concert and sporting events

11: The stadium's shimmering façade is composed of approximately 27,000 triangular aluminium panels

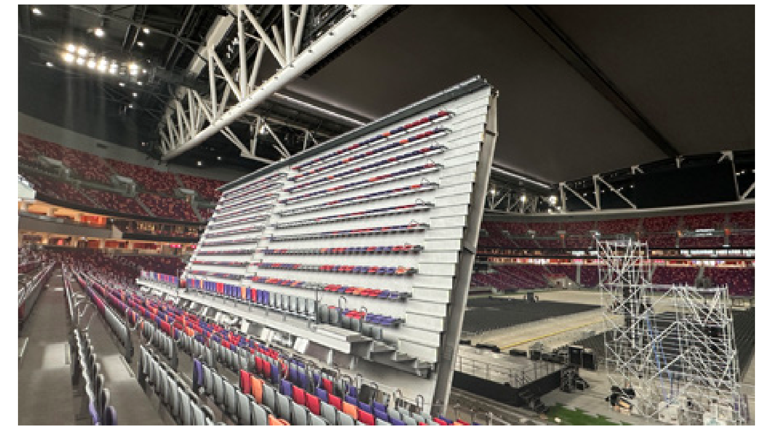
This process required intricate coordination with contractors, including the development of detailed mock-ups and meticulous cable management to ensure each light fixture could be individually maintained. This seamless collaboration, planning and execution resulted in a façade that is not only visually stunning but also aligns with sustainability goals.

Spectator movement and comfort

The stadium design prioritises comfort, safety and intuitive movement throughout spectator arrival and departure. To support efficient large crowd management, Arup's transport specialists used MassMotion – an advanced agent-based pedestrian 3D simulation software – to analyse pedestrian behaviours, factoring in varied walking speeds, crowd densities and accessibility needs for different groups of people. The analysis included night time and simultaneous events. Insights from these models guided the optimisation of circulation layouts and dispersal routes, ensuring smooth people flows and minimising noise impact during late-night exits. Pedestrian access is strategically set at podium level, allowing visitors to avoid busy vehicular traffic corridors at ground level at Shing Kai Road and Shing Fung Road. This approach enhances safety and overall visitor comfort while supporting reliable operation at scale.

The stadium bowl seating, constructed from over 2,000 precast concrete units, features individual cooling outlets at each seat, optimising both energy use and spectator comfort – crucial in Hong Kong's hot and humid climatic conditions. Arup conducted extensive airflow modelling to ensure adequate coverage throughout the stadium – using computational fluid dynamic simulations to fine-tune the system cooling the occupied layer of seating, striking the right balance between comfort and energy efficiency. In addition, a pitch cooling system maintains a comfortable environment for concert floor audiences without cold drafts and ensures safe temperatures for players competing on the pitch during sporting events. The air conditioning is powered by the Kai Tak district cooling system. The use of chilled water from the centralised district plant results in approximately 35% less electricity consumption than conventional air-cooled systems. Arup also performed sophisticated computer analyses to verify that the vibration comfort of spectators met international performance-based criteria for concert and sporting event scenarios.

The sports lighting system, mainly designed for football and rugby games, provides an exceptional visual experience for both live spectators and broadcast viewers. Strategically placed primarily along the roof perimeter, the lighting setup offers clear visibility of both players and the ball, reduces glare and ensures uniform illumination across the field. For TV broadcasts, the system achieves a brightness of 2,000lux, essential for capturing high-quality footage, with careful placement to avoid any lighting behind goals and maintain the best angles for comprehensive coverage.



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12: The stadium incorporates a section of seating in the southern end of the lower tier that hinges upwards, creating space for concert stages

13: The stadium is now established as a premier entertainment destination in Hong Kong

To protect the stadium from lightning damage, over 18km of copper tape was installed on the roof, equivalent to the perimeter of 50 football fields. This tape and the down conductor system provides a short path to the ground for lightning strike energy, protecting the building, occupants and system equipment.

The transformable stage

The stadium features an innovative stage pocket system at the southern end of the lower tier, a first in Hong Kong and one of the largest such systems in the world. It incorporates a section of seating that hinges upwards, creating space for concert stages and increasing the venue's capacity for large events. The system consists of four modular units: two large central units and two smaller side units. These can be operated independently, providing flexibility depending on the size and requirements of the event.

The stage pocket lifts into place using large hydraulic rams, securely locking once in position, with the concert stage typically constructed directly in front. This design not only simplifies stage setup by providing direct access from the vehicle loading dock to the stage area, facilitating efficient equipment transport, but also minimises damage to the pitch surface. Furthermore, fewer seats need to be removed during event setups, streamlining the process and reducing preparation time. The system was designed to integrate the stadium bowl's cooling ductwork beneath the seating. A gasket-and-seal system was used that automatically connects the ductwork when the stage is lowered,

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14: The Kai Tak Sports Park is a key part of the government's long-term strategy to promote sports development in Hong Kong and make the city a centre for international mega events

15: In the first year of operation, the stadium successfully welcomed over 1.9 million visitors

doing away with the need for manual dismantling or the requirement for any work in confined spaces.

Fire strategy

Arup delivered cutting-edge fire protection solutions and robust, forward-thinking fire safety strategies for the highly adaptable venue. By developing a fire safety strategy specific to the stadium's unique design and operational requirements, the fire risks associated with flexible layouts and large crowds were properly addressed. The firm conducted technical studies and quantitative engineering assessments to demonstrate the effectiveness of the proposed fire safety design. The team delivered advanced fire protection solutions, including state-of-the-art detection and suppression systems, as well as detailed evacuation plans accommodating various seating and staging configurations. With this fire safety design strategy, the number of smoke vents were reduced by over 40% from the prescriptive approach and there were significant improvements to the roof's acoustic performance.

The venue incorporates an addressable fire detection system. This precisely identifies fire locations, enabling rapid response. Integrated with remotely operated fire monitors – a first for Hong Kong – it can target specific areas with water, quickly controlling and extinguishing fires. This proactive fire safety system minimises risks to both attendees and the structure itself, offering a new approach for fire safety in public spaces.

Stadium success

A series of test events and stress tests took place in the venue in the first quarter of 2025, including a university rugby sevens

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tournament and a charity concert. Kai Tak Sports Park officially opened on 1 March 2025 and in the first year of operation, the stadium successfully welcomed over 1.9 million visitors. The venue has hosted a diverse range of events, including the annual Hong Kong Sevens rugby tournament (with 110,000 spectators in attendance over the three-day tournament), events in the 15th National Games, four sellout Coldplay concerts attracting nearly 200,000 spectators, three Hong Kong Asian Cup football qualifiers and the Hong Kong Football Festival – with Liverpool playing AC Milan and Arsenal facing Spurs.

At the core of the stadium's success is a truly flexible venue designed with purpose. Arup's design approach and dedication to excellence was instrumental in realising numerous Hong Kong firsts, establishing the Kai Tak Stadium as a premier leisure destination and a modern marvel in architectural and engineering design. More than a venue, it is a symbol of what can be achieved when technical excellence, collaboration and contextual thinking come together.

Authors

Henry Chan was the acoustic and lighting specialist. He is an Associate Director.

Vincent Cheng was the sustainability designer. He is an Arup Fellow and Arup's APAC Region Leader for Climate and Sustainability Services based in the Manila office.

Clement Ho was the designer for traffic works and crowd management. He is a Director and Arup's Southeast Asia Transport Planning Leader.

Anny Ip led the fire engineering design. She is an Associate Director.

Alvin Lam led the geotechnical design. He is a Director.

Ben Lam was the Project Director and project building services designer. He is a Director.

Bob Lau was the deputy building services designer. He is a Director.

Wei Lin led the structural design of the Kai Tak Stadium roof. He is an Associate Director.

Gordon Ng led the structural engineering design. He is a Director.

Calvin Siu was the Project Manager and led the south precinct structural team. He is an Associate Director.

Nina Yiu led the façade design. She is a Director.

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Project credits

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Jackson Zheng, Wendy Zhou, Evan Zhu.

Image credits

1: Highways Department,
The Government of the HKSAR
2-5, 7-9, 12, 15: Arup
6: Shots Around
10, 11, 13: Alex Lau (LT)/Arup
14: Kai Tak Sports Park Limited

Developing an investment strategy for resilient water systems

A decision-making under deep uncertainty approach is building water resilience in Ethiopia's Upper Awash Basin

Authors Francisco Fuenzalida Concha, Martin Shouler

1.

1: The importance of adopting a long-term perspective for strategic planning in the Awash basin is recognised within Ethiopian national development plans

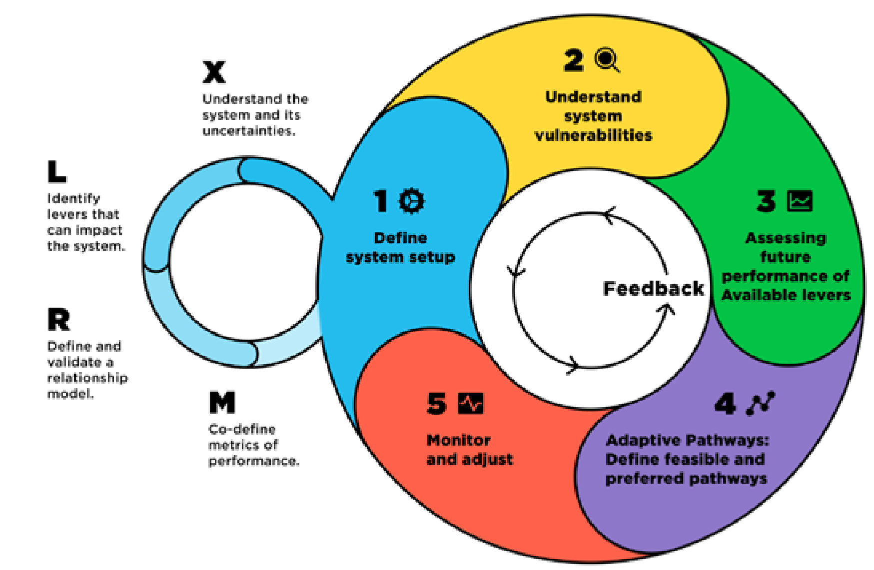
The Awash River in Ethiopia is a key water source for the nation's capital, Addis Ababa, and its surrounding cities. In this region, a reliable, resilient drinking water supply is essential to support residents, farmers' livelihoods, industry and climate resilience for future generations. But both rainfall and demand for water are highly unpredictable, with climate change, population growth, development ambitions and other uncertainties posing challenges for the region.

The importance of adopting a long-term perspective for strategic planning in the Awash basin is recognised within Ethiopian national development plans. Responding to this, Arup led a team that included Nexsys Analytics, HR Wallingford and Echnoserve, working together with Ethiopia's Ministry of Water and Energy (MoWE), to analyse the risks in the Upper Awash, upstream of Koka sub-basin (UAUK), and increase the resilience of the water supply in the region. Hundreds of thousands of plausible futures were assessed and, using this information, a phased adaptation roadmap and an investment strategy were developed.

An innovative methodology was used to look at the water security for this region. Enabled by increased computational power, the methodology did not just consider a small number of possible future scenarios but looked at the widest range across potential climate variable behaviours, as well as socio-economic variables including sectoral demands, population and land use. A decision-making under deep uncertainty (DMDU) approach was used to assess a large number of reasonable water supply and demand management options. This enabled the team to effectively consider interventions as portfolios of water solutions.

The DMDU approach helps clients make confident investment decisions by testing multiple options against a wide range of future scenarios. It reduces financial risk, strengthens business cases and can help unlock funding by enabling phased investment plans. The phased roadmap and recommendations that emerged from the analysis are now helping local decision-makers determine where, when and how to invest in maintaining and improving water systems between now and 2100. Drawing on funding from the World Bank, this will enable the ministry to reduce water losses and to take strategic decisions that will lead to a sustainable balance between water demand and supply.

The decision-making under deep uncertainty approach



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2: A decision-making under deep uncertainty approach assessed a large number of reasonable water supply and demand options

Understanding multiple challenges

It was important for the design team to understand the unique challenges this area of Ethiopia faces. The region has a highly stressed water system and is experiencing mounting pressure from rapid urbanisation and industrial growth. The location has a strategic importance to national development as it is the most populated basin, with both high domestic and industrial water demand – 60% of national industries are located in the region.

With a population of more than eight million and growing, including major urban centres like Addis Ababa and Sheger City, water demand in UAUK is intensifying. Away from the cities, water is also needed to sustain industry, agriculture and livestock.

Infrastructure deficits are significant, with non-revenue water (NRW) losses – treated and pumped water that is lost to the system due to leaks, unlicensed abstractions or non-paying users – nearing 36% and a supply gap of up to 60%. Deficiencies in public infrastructure and water system capacity have led to an overreliance on self-supply from groundwater, which has stressed groundwater sources with abstraction rates higher than the recharge of aquifers. With groundwater sources under such stress, investment is needed to conserve water supplies, tap into alternative sources of water and help to manage demand. But with so much uncertainty on the horizon – particularly in relation to rainfall

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> "The outputs of this work are useful to streamline governance and aid implementation, which is critical for the ministerial relationship with Sheger and Addis cities. MoWE plans to use the model and tools for future planning, which will help bring stakeholders together."
>
> **Debebe Deferso – Integrated Water Resources Management Lead Executive Officer, MoWE**

patterns and socio-economic shifts – the path to a secure and resilient water system is far from obvious and a fundamentally different approach to planning investment was required.

Arup drew on its experience developing both the City Resilience Index and the City Water Resilience Approach (CWRA). The index provides a comprehensive, technically robust, globally applicable basis for measuring city resilience, while the CWRA helps cities around the world grow their capacity to provide high-quality water resources for all residents and protect them from water-related hazards. The approach is designed to address water resilience challenges at a basin scale and has been applied in cities from Lagos, Rotterdam and Miami to Shanghai.

Preparing for different futures

The project team worked with MoWE to create a roadmap for improving water resilience by applying the DMDU approach to identify and assess intervention portfolios capable of performing well across a wide range of future scenarios. This included defining and modelling short-, medium- and long-term options (across 2020, 2060 and 2090) spanning infrastructure, policy and management measures.

The DMDU methodology to water resilience shifts away from traditional, fixed long-term planning towards more flexible, adaptive strategies. Rather than relying on forecasts and static assumptions, the approach acknowledges that the future, especially in the context of climate change, urban growth and political stability, is highly uncertain. It focuses on building robustness by identifying multiple agile pathways that can be adjusted over time as conditions change, using tools like adaptation tipping points and scenario planning. This enables water systems to remain responsive and effective across a wide range of possible futures.

The number of variables and the range of outcomes for each variable make attempts to predict and plan for specific conditions unwieldy and unworkable. Instead of attempting to forecast the future accurately and recommending a single course of action, DMDU is used to identify a whole range of different possible futures, and test potential infrastructure, policy and management measures against each of those futures. The approach can be used to shape a national or transnational strategy and was applied specifically on this project to the UAUK basin.

Using specialist hydrological modelling software and computing power developed within just the last few years, the project team were able to explore 60,000 possible futures (sampled from 388,000 scenarios of uncertainty) and the impact of different sequences of interventions in each. Sample interventions included building dams, fixing leaks in the supply network and a variety of demand management strategies, among others.

3: The Awash River in Ethiopia is a key water source for the nation's capital, Addis Ababa, and surrounding cities

4: Regular workshops were held with stakeholders to incorporate vital local knowledge and help validate findings

4.

A structured, five-step DMDU approach was used. This iterative method integrated locally available data with forward-looking planning, ensuring flexibility and alignment with the context in Ethiopia. The process began with scoping and a review of local development plans to inform the design of intervention scenarios. System configuration was defined using the XLRM framework. Exogenous uncertainties (X) included future sectoral demands (irrigation, livestock, industrial), population growth and climate-affected water availability. Policy levers (L) consisted of large-scale supply projects, rainwater harvesting, water management strategies and anticipated policy reforms. Relationships (R) were established using the open-source python-based PyWR model, built on local allocation systems and enhanced hydrologic inputs. Performance metrics (M), shaped by stakeholder input, covered cost (both capital and operating), reliability, environmental impact and readiness.

Arup worked with stakeholders in UAUK to build local development plans, priorities, performance metrics and potential policy levers into the model. Regular workshops were held with stakeholders including MoWE, the World Bank, Addis Ababa Water and Sanitation Agency, and academics from Addis Ababa University. The workshops helped validate findings, incorporate vital local knowledge, ensure alignment with institutional capacity, and take account of the political, economic and geographical context in the recommendations.

By testing the water system against a wide range of future scenarios, the process identified vulnerabilities and performance gaps. Insights from this analysis guided the development of targeted interventions.

5: The project team explored 60,000 possible futures sampled from 388,000 scenarios of uncertainty

6: The DMDU approach enables water systems to remain responsive and effective across a wide range of possible futures

5.

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Multi-criteria and sensitivity analyses were used to evaluate these interventions, quantify outcomes and highlight trade-offs. The most effective options were grouped into adaptive pathways, each defined by conditions under which they may fail, and consolidated into a phased roadmap outlining short-, medium- and long-term strategies.

The collaborative method used produced a robust set of recommendations and a shared roadmap for long-term water resilience in a deeply uncertain future. These are being used to support decision-making by providing information to help focus investment into projects supporting resilience and to identify, from the options explored, the logical next steps in a timely manner.

Managing demand for water

The assessment highlighted critical vulnerabilities within the UAUK basin's water system. The analyses revealed expected high water demand as the primary driver for potential system failure, with the scale of planned future demand surpassing potential supply gains from the considered interventions. Consequently, demand management strategies, including

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7: Arup led a team to analyse the risks in the Upper Awash, upstream of Koka sub-basin, and increase the resilience of the region's water supply

8: The tools and processes developed for the UAUK basin are already supporting local decision-makers

9: Arup drew on its experience of developing the City Water Resilience Approach, which has been applied in many cities around the world, including Rotterdam

10: Rainfall and demand for water are highly unpredictable, with climate change and population growth posing particular challenges

increased metering ratios, reduction of NRW and water abstraction regulations, are deemed crucial.

Addressing the root causes of rapidly increasing demand was recommended as a complementary intervention alongside demand control measures. This involved reassessing the proposed locations for future industrial developments and generating incentives and policies to direct demand increase to areas with abundant water resources.

In addition, recommendations such as scaling up low-yielding interventions and increasing investments to develop new water sources were suggested. A few straightforward recommendations were proposed, such as the introduction of a new water tariff system in order to reduce government subsidies and redirect the funds towards the proposed interventions.

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Short-term recommendations also included a focus on NRW reduction and wastewater reclamation, while medium- to long-term recommendations included proposals for large water transfers, improvements to water governance systems to allow for more effective demand management and establishment of detailed plans for financing interventions. Grouping options into adaptive pathways suited to the different plausible futures gives a flexible roadmap to a more sustainable future.

The most effective options were grouped into adaptive pathways, each defined by conditions under which they may fail (such as demand and supply availability) and consolidated into a phased roadmap outlining short-, medium- and long-term strategies. These strategies provide a clear picture of the options for investment. This can be used by MoWE, and by external organisations such as the World Bank.

The DMDU approach enables water systems to remain responsive and effective across a wide range of possible futures. Continued evaluation and adaptation were recommended to maintain resilience in the face of emerging risks and future uncertainties. If conditions such as economic activity change, or if more detailed information becomes available, then the model can be re-calibrated. This will generate new recommendations to ensure that investment choices help the water system to remain as resilient and robust as possible, whatever the future holds.

Arup also helped build capacity among key departments and academics in Ethiopia. Sharing the firm's experience, open-source tools and processes means that local teams can use, review and adapt the pathway as needed. The firm's experts have offered ongoing support to help maintain the model and support new users.

The learnings

Throughout the project duration, the team identified factors crucial to the success of the process. Firstly, continual engagement with stakeholders was essential. Their input helped to ensure the use of the best available information, which is especially valuable in data-scarce contexts, and to improve the accuracy and credibility of results. Regular feedback loops also built trust between stakeholders and the delivery team, increasing confidence in the findings and facilitating uptake of the project outputs.

Secondly, the active role of local academic institutions brought dual benefits: it enabled access to deep local knowledge and system insights, while also promoting institutional learning. Local academics were directly involved in co-developing key aspects of the work, such as modelling and multi-criteria assessments. This not only strengthened technical inputs but also fostered local ownership, helping ensure long-term continuity and responsibility for the solutions.

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The systems approach, looking at policies, management and infrastructure interventions, allowed the team to identify linked opportunities and highlight innovative ways to enhance resilience and direct efforts effectively. This integrated perspective made it possible to align interventions across multiple sectors and timeframes, enhancing the overall effectiveness of the roadmap.

The tools and processes developed for the UAUK basin are already supporting local decision-makers. They can now be confident they are taking evidence-based action that will help to safeguard the water supply for millions of people. The team have applied the methodology elsewhere, including for the Genale Dawa Basin south of Addis Ababa and for developing a strategy for prioritising resilient water sector investments in Botswana. Arup has also shared this approach with a wide range of collaborators, including C40 Cities.

10.

Authors

Martin Shouler was the Project Director. He is a Director in the London office.

Francisco Fuenzalida Concha was the Project Manager. He is a Senior Engineer in the London office.

Project credits

Client The World Bank Group

Partners and collaborators Nexsys Analytics, HR Wallingford, Echnoserve, Ministry of Water and Energy, Addis Ababa University

Water engineering Arup: Sersha Barry, Francisco Fuenzalida Concha, Benedict Krueger, Matthew Phillips, Cassia Pickard, Martin Shouler, Kirsten Smith, Philip Songa, Phillipa Stanley, Wanja Wamae.

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1.

Lowestoft's landmark bascule bridge

Innovative design has delivered a unique bascule bridge that is improving connectivity and providing regeneration opportunities

Authors Gary Crisp, Conor Lavery

Lowestoft – the most easterly town in the UK – is split in two by Lake Lothing. Before Gull Wing Bridge was constructed, movement from the north to the south of Lowestoft was curtailed by the frequent opening of two existing crossings at the eastern and western extremities of the saltwater lake – with the eastern bascule bridge at the entrance to the inner harbour of the Port of Lowestoft opening for every vessel entering the port. The delays to road traffic resulted in severe congestion that was an impediment to the economic vitality of the town and the wellbeing of its residents.

The aim of building a third bridge was to introduce a more reliable crossing that opened far less frequently. This would dramatically alleviate traffic congestion and transform the lives of local people and businesses by stimulating regeneration, sustaining economic growth and reinvigorating Lowestoft as a place to visit, live and work.

Gull Wing Bridge, situated between the two pre-existing bridges, comprises a 350m-long eight-span viaduct that crosses the East Suffolk railway line and Lake Lothing within the Port of Lowestoft. The project included approach embankments, a control tower, a plant room and connecting roadworks at either end, linking in with the existing main road network in the town. The bridge now diverts the A12, forming a key part of the road, which connects to Ipswich. Since Gull Wing Bridge opened to the public in September 2024, it has successfully alleviated traffic congestion in the town centre, while also providing a new pedestrian- and cycle-friendly crossing linking north and south Lowestoft. Traffic figures indicate that there has been a 47% reduction in total vehicle movements over the existing eastern bascule bridge in the centre of the town with a significant reduction in heavy goods vehicle movements.

1: It is the largest rolling bascule bridge in the world using this form of mechanism

2: The bridge forms a key part of the A12 from Ipswich to Lowestoft

The centrepiece of the new crossing is a rolling bascule bridge with a span of 38m. When the bridge is lifted, it provides a 32m-wide clearance for the maritime navigational channel. Raised using hydraulic cylinders, it is the largest rolling bascule bridge in the world using this form of mechanism. It requires a meticulously balanced centre of gravity for operation. The design concept could only be realised by using innovative heavyweight concrete and overcoming numerous technical and practical challenges.

An integral part of the design brief was to deliver transformational change for the town, in addition to minimising the environmental impact of the scheme. This resulted in the decision to adopt a rolling bascule bridge mechanism – an inherently beautiful and elegant kinematic form that inspired local primary school children to name the crossing for its resemblance to seagull wings.

The bridge sits 12m above the highest astronomical tide level, enabling small craft to pass under the bascule span. For larger vessels, the bascule bridge element rolls back onto the southern steel concrete composite approach viaduct, which is a novel solution. This presented numerous challenges, all of which the design overcame, including deformation, fatigue, construction tolerance and the requirement to pump hydraulic oil approximately 80m from the control building to the cylinder manifolds.

Construction was led by Farrans, with Arup supporting Suffolk County Council (SCC) as the lead designer and technical advisor overseeing the completion of the project to the high standards required.

Boundary-pushing piling

The bridge has a 148m-long north approach viaduct with three spans, the most northern of which crosses the railway, and a four-span south approach viaduct that is 154m in length. Two of

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the bridge's piers sit in the water and five on land. Construction began in spring 2021 with conventional contiguous flight auger piling and reinforced-concrete pile caps for the land-based substructures. For the marine piers, a combi-wall cofferdam consisting of alternating sheet piles and 1.22m-diameter steel tubes was driven to -14mOD in the lake. The steel tubes were used as casing for the construction of rotary-bored reinforced-concrete piles to depths up to -62.5mOD.

The use of polymer support fluid for constructing such deep piles in granular sand was groundbreaking, presenting numerous challenges such as the requirement to stabilise bores overnight due to long piling durations, and maintaining polymer fluid pressures amid tidal fluctuations in the lake. Site constraints made trial piles prohibitively expensive, so Farrans, Quinn Piling and KB International collaborated closely with SCC and Arup to manage these risks through a robust piling method statement, with clear monitoring points, polymer testing regimes and predefined mitigations for any findings to ensure excellent construction quality.

Sonic logging of the first five piles and four randomly chosen piles demonstrated the success of the boundary-pushing construction method and the controls put in place. With sustainability in mind, the cofferdams were designed to participate in the permanent works, in addition to their temporary works role. This imposed construction challenges, particularly for the southern marine pier, where the concrete 'wet plug' cast underwater had to be reinforced and anchored to the combi-wall cofferdam. Under the supervision of specialist divers from Norfolk Marine, steel reinforcement cages assembled on land were lifted into the cofferdam and concrete was pumped into a series of strategically distributed tremie pipes to ensure adequate concrete placement.

Reinforced-concrete pile caps and piers were constructed inside the de-watered cofferdam. All piers across the site were constructed with limestone aggregate,


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3: Construction began in spring 2021 with contiguous flight auger piling

4: One of the viaducts spans over the East Suffolk railway line

5: The bridge sits 12m above the highest astronomical tide level


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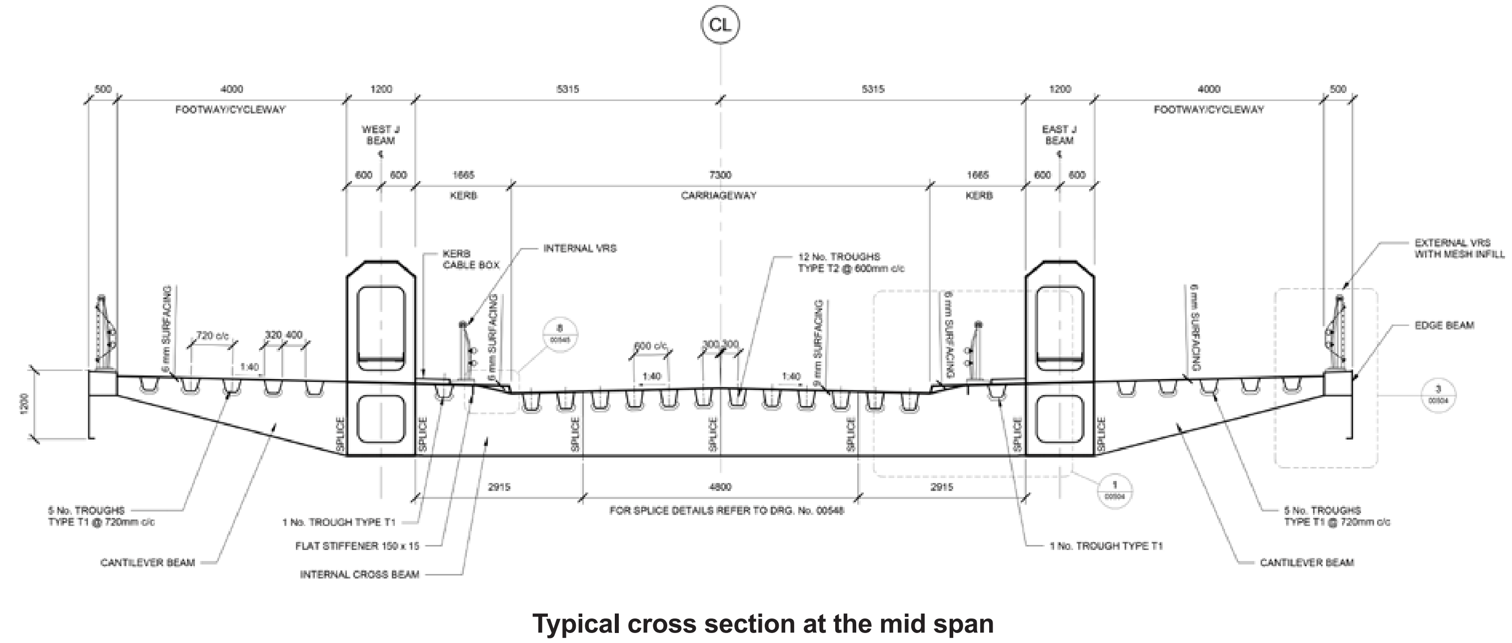
while silica fume was also added to the marine piers to improve durability in the harsh environment. Close coordination with the port owner and the Environment Agency ensured minimal disruption to marine traffic and marine ecosystems during construction.

Approach viaducts

Both the north and south approach viaducts are made up of steel composite girders with a concrete deck on top. Throughout 2022 and 2023, steel fabrication of the viaducts and the bascule bridge was carried out by Victor Buyck Steel Construction in Belgium. Each span was delivered to site by barge – a carbon-effective delivery method – passing through the existing twin-leaf bascule bridge at the entrance to Lake Lothing from the North Sea.

From the outset, the project embraced key principles of Publicly Available Specification (PAS) 2080 – the standard for carbon management in infrastructure. The team adopted the carbon reduction hierarchy (avoid, switch, improve) to integrate carbon considerations into decision-making. For the 310m of approach viaducts, a switch from a cast in-situ post-tensioned concrete box girder viaduct to composite steel concrete ladder beam deck resulted in a 14% reduction of emissions (approximately 2,300tCO_2e).



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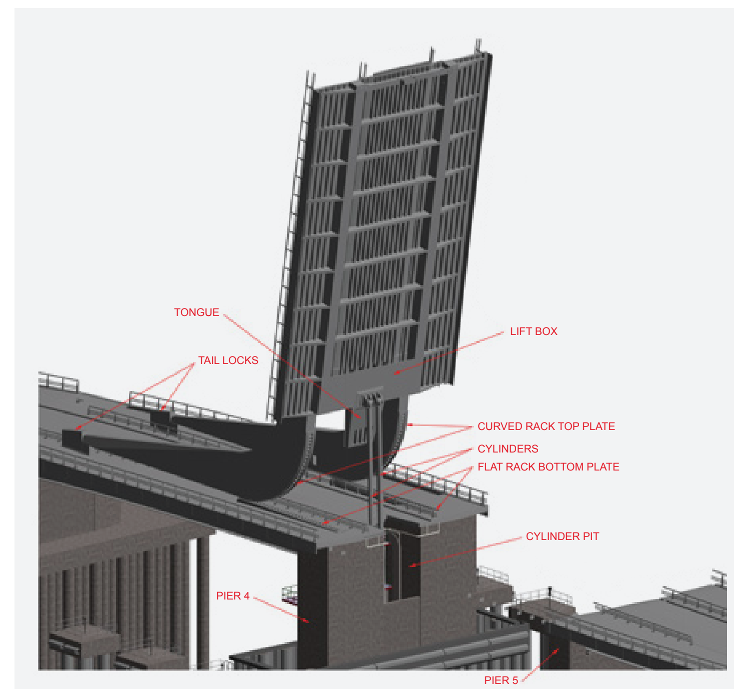

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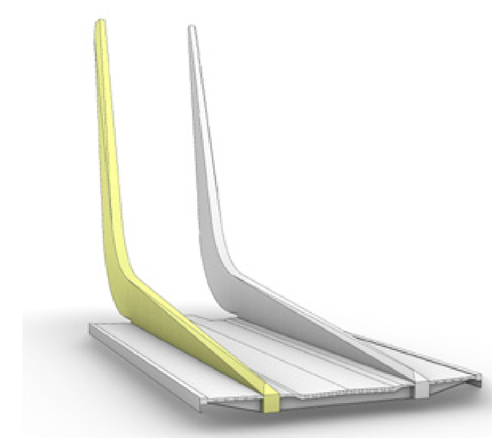
6: The bridge provides a new pedestrian- and cycle-friendly crossing linking north and south Lowestoft

7: As the bridge opens, hydraulic cylinders housed within the marine pier push on the soffit of the bridge deck

8: Gull Wing Bridge comprises a 350m-long eight-span viaduct

9: The bridge was given its name by local children due to its resemblance to seagull wings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At the detailed design stage, a further 30% reduction in emissions was achieved by optimising steel sections, using advanced finite element analysis for fatigue design and, where possible, making use of temporary works in the permanent works. As a result, the northern approach viaduct achieved an up-front carbon footprint of 1,900 kgCO_2e/m², a 25% lower carbon intensity than typical steel composite highway bridges. The southern approach viaduct achieved an up-front carbon footprint of 3,100 kgCO_2e/m², the design being driven by the requirement to support the rolling bascule bridge in operation. Arup used a parametric grasshopper script to define the minimum number of bespoke precast planks


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required to suit the curved alignment with varying bridge width. A similar approach was adopted for the precast concrete parapet edge beam units.

The northernmost approach span over the railway line was the first to be erected. After delivery to site, the steelwork was placed on temporary supports to cast the in-situ concrete deck and install the precast concrete parapets, thereby avoiding work over the railway and improving safety on site. Self-propelled modular transporters manoeuvred the completed span into place over a weekend railway possession in October 2022. Effective planning and collaboration with all parties ensured the railway line reopened on time.

The other six approach spans were erected by crane. The southern span over the lake, weighing 381 tonnes, required one of the largest cranes in Europe, Terex Demag CC8800-1, to manoeuvre the span into position. The crane arrived by ship from Denmark directly into Lake Lothing, minimising its environmental impact; more than 100 heavy goods vehicle loads would have been needed to transport it by road.

Bascule bridge element

Environmental and aesthetic considerations, along with the operational requirements of the Port of Lowestoft, ruled out the construction of new quay walls and large below-deck bascule chambers within the lake. Such


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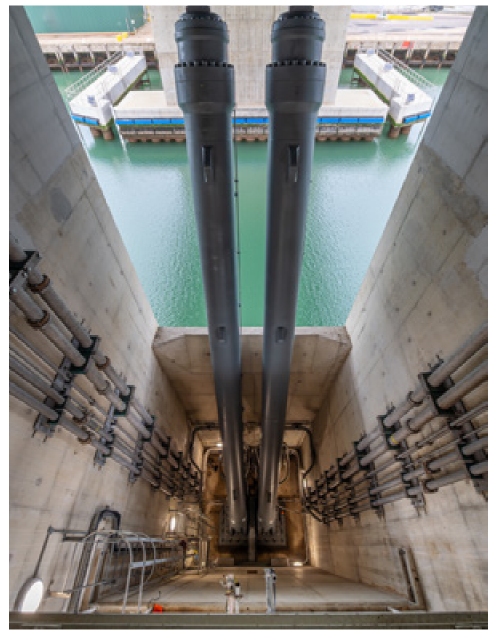
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10: Self-propelled modular transporters manoeuvred the completed span over the railway during a weekend track possession

11: Terex Demag CC8800-1 – one of Europe's largest cranes – lifting the 381-tonne southern span into place

12: The bridge opening is facilitated by a curved rack plate fixed to the soffit of each of the J beams and by flat rack plates fixed to the southern deck

13: The hydraulic cylinders that operate the bridge are protected against a one-in-10,000-year flood event

structures, required for more traditional moving bridge forms, would have narrowed the navigation channel and raised flood levels in the surrounding areas. These critical requirements made a rolling bascule bridge the optimal solution, as it places all principal structural elements above carriageway level and affords a multitude of possibilities to showcase the motion and structural detailing of this bascule form.

Critical to the success of this project was the careful control of the centre of gravity of the bascule bridge, which drives the operational efficiency, reliability and power requirements. The weight of the bascule steelwork and all ancillary items was precisely


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14: The bridge has a 148m-long north approach viaduct with three spans

15: When the bridge is lifted, it provides a 32m-wide clearance for vessels

balanced with 92.5m^3 of heavyweight concrete. Particular focus was placed on the installation of the hydraulic cylinders to the soffit of the bridge, the placement of flat rack plates to align with the curved rack plates during rolling, and ensuring engagement of the wing-shaped J beams with the tail lock when the bridge is fully open.

Design of the rolling bascule bridge was optimised and meticulously calibrated through parametric analysis of more than 50 design scenarios, linking a grasshopper/rhino script to the structural analysis finite element models. This approach enabled steel plate thicknesses and weld sizes to be optimised rapidly. The rhino models were used exhaustively to determine the preferred sequence of fabrication of the box girder elements, which in turn dictated the steelwork details.

The design of the bascule bridge was driven by fatigue, with the bridge built to withstand opening 10 times a day across a 120-year design life. Detailed finite element analysis models were set up for various degrees of opening of the bridge. A bespoke python script was developed to extract the stresses from each model for a set of load combinations in order to automate the fatigue cumulative damage verification.

Hydraulic cylinders housed within the marine pier push on the soffit of the bridge deck. This causes the centre of rotation of the bascule to move horizontally backwards as it opens, facilitated by a curved rack plate fixed to the soffit of each of the J beams and by flat rack plates fixed to the deck of the southern steel composite approach viaduct. As the point of support of the bascule is constantly changing as it rolls back and forth, rolling bascule


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bridges are typically supported on rigid concrete substructures. In this case, the necessity to roll back onto the flexible approach span introduced significant fatigue stress fluctuations in all structural elements, including cyclic degradation of the pile shaft resistance. There was a need to minimise structural rotations and displacements in order to not adversely impact the operational performance of the bascule. The hydraulic oil, hydraulic power units and backup generator are remote from the hydraulic cylinders, which involves pumping oil 80m from its storage tank, all while being able to open the 1,130-tonne bridge in less than two minutes up to 10 times a day. Testing and commissioning took place over a period of four months to replicate various scenarios, verify design assumptions and finely tune equipment setup and operational control.

Critical to the feasibility of the entire project was minimising impact during construction on the port operations and on the East Suffolk railway line to Lowestoft Station. This required developing construction techniques and sequencing at the design stage that could demonstrate that the bascule bridge could be floated and lowered into position, the heavyweight concrete counterweight placed, the mechanical rack plates installed and the rolling bascule bridge rotated to a fully open position, all within a non-negotiable three-week construction window.

Counterweight solution

A key aesthetic ambition for the bridge was to avoid the large counterweight compartments at height linking the two wings that are typical of bascule bridges. The solution to this was to encase the counterweight within the envelope of the striking structural wing-shaped J beams, thereby expressing the engineering principles of the moving bridge mechanism rather than hiding them below deck.

A bespoke heavyweight concrete mix design with a dry density of 4,077kg/m^3 was developed, making use of magnetite aggregate to achieve the required counterweight within the volume available in the beams. This required close collaboration between SCC, Arup, Farrans, Capital Concrete, LKAB Minerals and Camfaud Concrete Pumps to achieve the heavyweight concrete needed to meet the design criteria. The material needed a specific density, both at the batching plant and upon arrival on site, with consistent wet and dry densities. It would be pumped to a height of 30m above the bridge deck to enable placement and to flow down the internal height of the steel wings without any aggregate segregation over the 16.2m pour height.

The three-week window available to position the bascule bridge, balance the bridge and have it operating meant that the contractor had only one day to place the counterweight. A full-scale mock-up of the heavyweight concrete pour took place four months before the date of the actual pour to give confidence that the specification was achievable. If issues had arisen during the actual placement or with achieving the correct density, the implications for the programme and cost would have been enormous.

The bascule element was the final piece of the bridge to be installed in March 2024. Before delivery, the final assembly was carried out in the Netherlands, together with rigorous mass and geometry checks. The curved portion of the J beams was milled to form a perfect contact surface with the flat rack plates on which the whole bridge rolls. The assembled bridge was then transported to Lowestoft by barge, from which it was jacked up and lowered onto the two marine piers.

Quick facts

- Counterbalanced rolling bascule bridge
- Total weight 1,130 tonnes
- Raised by two hydraulic cylinders
- Designed to open 10 times a day
- 120-year design life
- Opening cycle of 116 seconds

Climate resilience

The effects of rising sea levels, higher intensity rainfall events and increasing summer temperatures were considered throughout for each individual aspect of the design. The bridge drainage system allows for a 40% increase in rainfall intensities, with the pipe sizing accommodating a one-in-100-year rainfall event with a six-hour storm duration. The bridge, protection dolphins and fendering were designed to consider a 1.54m rise in sea levels over the next 120 years based on UK CP09 climate projections.

The control tower and all plant areas were designed to be protected from a one-in-200-year flood event, accounting for worst case future climate change scenarios. The power to the electrical substations which feed the bridge has a diversity of supply from two different sources and there is a backup generator, while the bridge is designed to operate on a single cylinder if required. The hydraulic cylinders which operate the bridge are protected against a one-in-10,000-year flood event, with allowance for climate change.

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16: The drainage system can withstand a one-in-100-year rainfall event with a six-hour storm duration

17: The 1,130-tonne bridge is designed to open in less than two minutes

Community value

Throughout construction, the project team delivered a bespoke social value delivery plan, including educational outreach, local volunteering, community engagement events, site visits, work experience and over 25 opportunities for local apprentices and graduates. This represented a significant first step in achieving long-lasting social value and a positive impact on the community. All of the above contributed to a significant return on investment based on social value using the UK standard National TOMS measure, which was greatly appreciated by the local community.

The crossing includes 4m-wide foot and cycle paths either side of the new road, physically connecting the walking and cycling networks in north and south Lowestoft and providing an attractive new active travel route with the potential to improve health and wellbeing.

Performance

Gull Wing Bridge has been warmly embraced by locals, transforming their journeys, alleviating traffic congestion and affording an opportunity to re-imagine the centre of Lowestoft. On a typical day, vessels require the bridge to lift three times, with an average duration of only six minutes per bridge opening. Data collected from the first six months of service show that local journey times have reduced significantly, meeting the reliability and operability objectives of SCC.

From the unprecedented depths of marine rotary-bored piling under polymer support fluids, to the towering heights of boundary-pushing crane lifts, Gull Wing Bridge showcases the extremes of construction excellence. Achieving smooth operation of the world's largest rolling bascule bridge operated by hydraulic cylinders required world-class collaboration across the project team and contractor's supply chain, expert craftsmanship to meticulously control construction quality and tolerances, and a dedication to deliver.

17.

Authors

Gary Crisp was the Project Director for Arup. He is a Director of Major Projects and based in the Nottingham office.

Conor Lavery was the Project Manager for Arup. He is an Associate Director in the London office.

Project credits

Client Suffolk County Council
Architect Moxon Architects
Mechanical, electrical, instrumentation, control and automation (MEICA) engineer Eadon Consulting Ltd
Drainage engineer MLM Consulting Engineering Ltd
Contractor Farrans Construction
MEICA Contractor Oilgear UK Ltd
Building Services Contractor DPL Group
Steelwork fabricator Victor Buyck Steel Construction
Steelwork installation Mammoet and HEBO maritime
Piling contractor Quinn Piling (Rotary) and PJ Edwards & Company (CFA)
Earthworks contractor Deep Soil Mixing Ltd
Bridge, civil, environmental, geotechnical, highway, lighting and ITS, maritime, mechanical, electrical, and public health engineering Arup: Ali Abood, Andrew Allsop, Luca Amerio, Rabin Annauth, Lukasz Bies, Chris Bolt, Emma Boucher, Connor Braithwaite, Thorsten Braun, James Bristow, Jay Browning, Alberto Carlucci, Chris Carrod, Rebecca Casey, Honoury Cheung, Paul Clenahan, Nick Combes, Chris Corr, Gary Crisp, Lucy Cryer, Tom Culleton, Matt Cumberbatch, Leire De Mariscal Perez, Nick Dibben, Nigel Dore, Nigel Dunn, Berkan Ergun, Joe Fenn, Solene Fercocq, Lamar Fowakes, Emily Fung, Edward Gamblin, Elena Gavazzi, Adrian Gibbs, Alison Goddard, Ned Gould, Lucas Hafkenscheid, Alan Hake, Adrian Hall, David Hayes, Chris Heath, Chris Heighton, Lewis Hobbes, Joe Hogarth, Conor Holliday, Richard Hornby, Cameron Hughes, Syed Hussain, Michel Junior Ishak, Ed Kell, Sebastian Kiergassner, Conor Lavery, Greg Leonard, Joanna Lubkowska, Shane Mann, Athanasia Marinou, Giulia Matteoni, Isobel McClure, Umesh Mistry, Tim Morgan, Joseph Murphy, Greg Murray, Duncan Nicholson, N Nisha, Ciara Norris, Raluca Olariu, Abir Osman, Mike Owers, Neil Perry, Mina Pogia, Christopher Price, Stefan Rankovic, Scott Reid, Andrew Rogers, Adam Ross, Erin Ruddy, Raminta Rudzeviciute, Robert Salca, Ione Sandberg, Hiroshi Sasano, Stephen Scott, Hannah Shewan-Friend, Eleanor Sinkinson, Anna Stewart, David Stewart, Jamie Temple, Chris Tong, Ana Ulanovsky, Daniel Urrea Perez, Joan Valls Mestre, Chris Van Lottum, Amedee Vautravers, Tanay Verma, Arush Wadhwa, Alexandra Wallis-Evans, Kelvin Ward, Sally Wells, Joe Westhead, David Wilde, Ian Wilson, Jonas Winterhalter, Daniel Wren, Brian Yates.

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Cultivating a net-positive future

The transformation of the Marie Selby Botanical Gardens has created a facility that both withstands and supports the environment it inhabits, while producing more energy than it consumes

Authors John Hand, Hussein Moussa, Linda Toth

Located on Sarasota Bay in Florida, the Marie Selby Botanical Gardens is one of the world's first botanical garden complexes to be energy net positive. The landmark achievement marks the completion of the first phase of a multi-year masterplan to transform the site into a model for sustainable research, education and visitor engagement.

Arup worked in collaboration with architecture firm Overland Partners, landscape architecture firm Olin Studio, and civil engineering consultants Kimley-Horn, to deliver a series of new facilities including three new buildings that balance technical performance with environmental stewardship. The firm provided structural, mechanical, electrical and public health engineering design, along with energy, sustainability, acoustics, lighting and technology consultancy services. The result is a campus that has been optimised for energy efficiency so that the on-site solar photovoltaic (PV) array produces more energy than the campus consumes on an annual basis, while strengthening resilience against future climate events.

Central to phase one of the campus expansion is the Morganroth Family Living Energy Access Facility (LEAF), a 188,000ft^2 (17,500m^2) complex that includes parking, a restaurant and a gift shop, topped by a 877kW DC rooftop solar PV array. The system is expected to generate 5% more energy than the site's projected energy use, which will allow Selby Gardens to operate as a net-positive campus. Alongside the LEAF and adjacent Jean Goldstein Welcome Center, the Steinwachs Family Plant Research Center provides advanced facilities for plant research, conservation and public learning.

1.

1: Three steel quadripods support the canopy of the Welcome Center

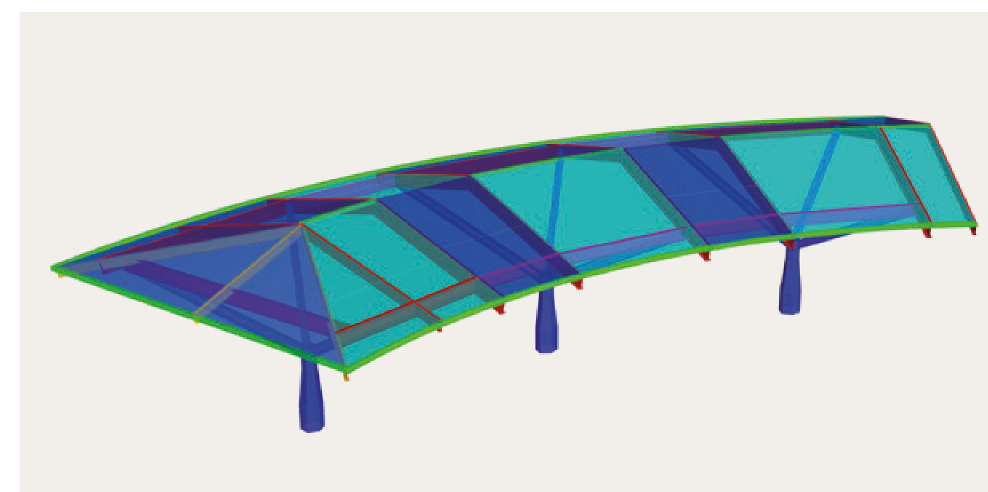
2: 3D Rhino modelling was used to define the roof geometry

The masterplan, initiated in 2017, set out to increase green space on the site, enhance water access for eco-tours, and create a demonstration platform for regenerative technologies, such as rain gardens, rooftop food gardens and stormwater reuse. It also sought to consolidate the gardens' global reputation for orchid and epiphyte research, with new laboratories and a modern herbarium designed for long-term durability and resistance against extreme weather events in an existing high-climate-risk site location.

Through close work with the client and design partners, Arup helped translate an ambitious sustainability vision into practical, buildable outcomes. Despite challenges including the COVID-19 pandemic, multiple hurricanes and local construction constraints, the team delivered a project that shows how infrastructure for culture, science and leisure can contribute positively to the environment.

A vision rooted in nature

Arup contributed to these new facilities, which incorporate sustainability standards from the International Living Future Institute's (ILFI) Living Building Challenge (LBC). Living Buildings are regenerative buildings that connect occupants to light, air, food, nature and community, are self-sufficient and remain within the resource limits of their site, and create a positive impact on the human and natural systems that interact with them. The project is certifying these buildings together, with the Living Community Challenge platform used to track Petal certification in three of the seven imperatives – Energy, Place and Beauty. In addition to the design requirements, the certification also requires a 12-month operational compliance period to demonstrate energy performance.



2.

Arup helped implement a range of sustainable design solutions, including the advanced solar field structure, a rooftop edible garden and increased flood resiliency for the Plant Research Center.

One of the team's inspirations for its design philosophy was the epiphytes and orchids that are housed at Selby Gardens as part of a collection of more than 20,000 living plants. The project aimed to protect them and build structures that could coexist with and support their environment, rather than dominate it. Arup focused on this principle in guiding the architectural and engineering approach, while accounting for the client's goals of increasing green space, improving visitor experience and creating a site for regenerative design.

The design of the new campus draws inspiration from the natural systems that Selby Gardens study and protect.

The facility is globally recognised for its work with orchids and epiphytes, plants that grow on trees without drawing nutrients from them. This idea of coexistence guided the design approach, creating buildings that support and interact with their surroundings rather than dominate them.

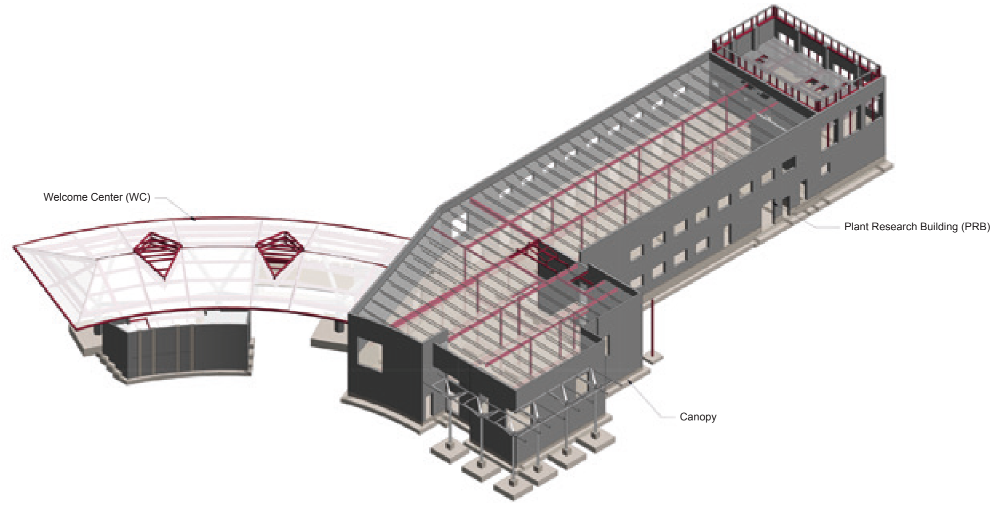
Arup and Overland worked closely with the client to translate this vision into a set of clear sustainability goals. The first phase of the redevelopment aimed to increase the site's green space, improve visitor flow and integrate new infrastructure within the landscape. Each component was developed to minimise environmental impact, enhance biodiversity and make the most efficient use of resources.

Selby Gardens' leadership, supported by hundreds of volunteers, determined that the new facilities should extend rather than disrupt their mission. Arup aimed to have every new structure functioning as part of the broader living system of the gardens. This thinking informed every stage of the masterplan.

The Welcome Center, originally designed as a glass building, was reimagined as a lighter, open-air structure to reduce material use, conditioned space demands and cost. Arup initially conceived a steel structure following the form of an orchid before the design was revised to an expressed structural form inspired by the trees of coastal Florida and how they resist hurricanes. Three steel 'quadripods' were used for the structure, with each quadripod having a root (foundation), trunk (main column), branch (beams) and canopy (roof) structure. Arup used 3D Rhino modelling to define the roof geometry and worked in collaboration with the architect to create uniformity in the quadripods and framing for the roof. The design also allows plants to hang and grow from the canopy itself, creating a direct visual link between the garden and the built form.

Similarly, the LEAF facility and the Steinwachs Family Plant Research Center were designed to fuse performance and ecology. Both buildings use natural light and mixed-mode ventilation strategies, while their materials and structural elements were designed to withstand hurricane conditions. Design iterations for the LEAF went through multiple changes to respond to community concerns and amend the biophilic design to blend with the neighbouring residential community. The project also elevates key systems and collections above flood zones and has on-site solar photovoltaics plus battery storage, improving long-term resilience to extreme weather.

By aligning architectural design, engineering and landscape planning, the team met the challenge of ILFI's intent to restore the balance between the natural environment and the built environment. This integrated approach was critical as the project progressed into detailed design and construction, where the team faced a series of technical and logistical challenges. The project required careful cost management, coordination across disciplines and ongoing engagement with local contractors to push the boundaries of high-performance, sustainable design.



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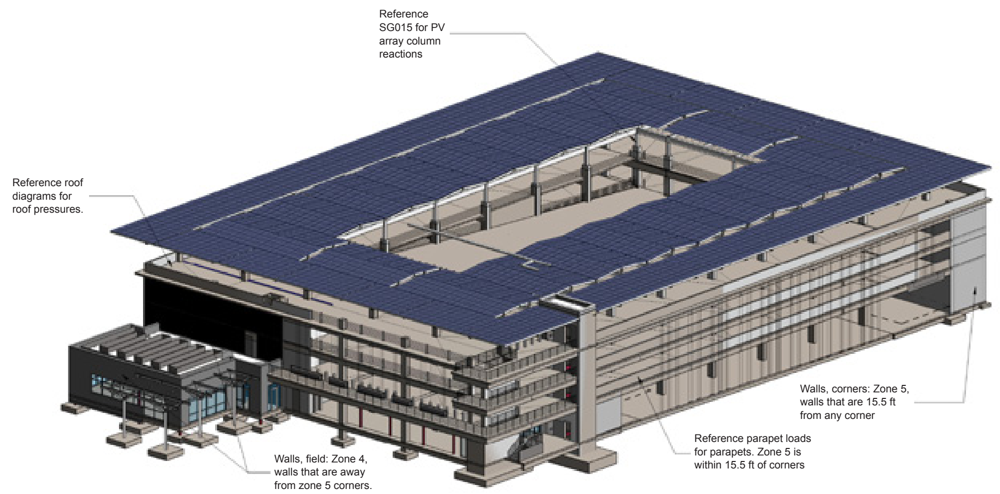

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3: The Welcome Center is connected to the Plant Research Building

4: The LEAF stands at the centre of the new campus

5: The PV array is made up of 2,158 panels

6: The quadripods have an expressed structural form inspired by the trees of coastal Florida and how they resist hurricanes

7: The structure elevates the most critical collections to the second floor, providing an additional 4m of flood protection

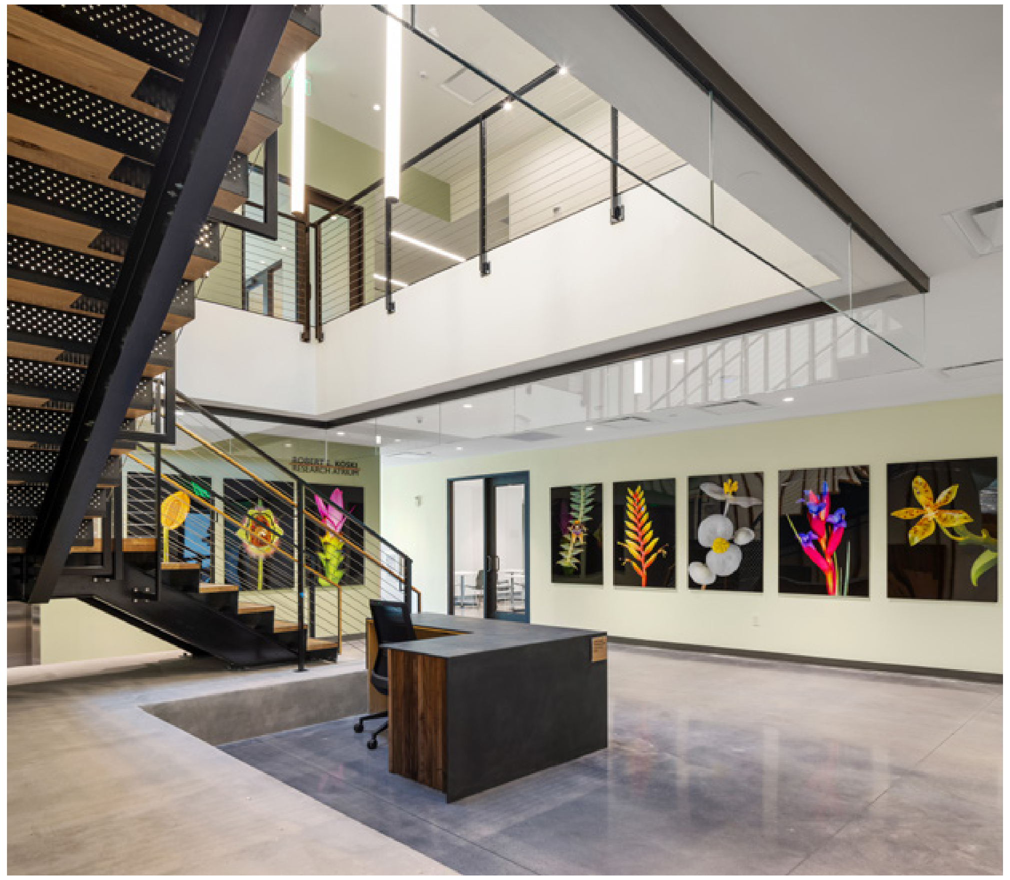
Engineering the LEAF

The Morganroth Family LEAF stands at the centre of the new campus as a multi-purpose structure that embodies the project's commitment to regenerative design. Combining a restaurant, gift shop and multi-storey car park, the roof also houses a 2,158-panel solar PV array designed by One80 Solar. It produces clean energy for both the LEAF and Plant Research Center buildings.

Arup's engineering and sustainability teams worked to ensure that the LEAF would meet the 105% annual energy demand requirement for ILFI. The array, one of the largest in the region, is rated to produce around 1.27MWh of electricity each year.

This production is anticipated to meet the 5% net-positive energy surplus based on detailed energy demand calculations. To achieve this performance, every piece of equipment, from laboratory freezers to kitchen appliances, was catalogued and modelled to understand its energy profile.

One of the biggest challenges was meeting the restaurant operator's requirements while setting up the facility's all-electric kitchen for a full-service restaurant. The world's first net-positive restaurant has been delivered by scaling down total energy demand through close coordination between Arup's engineers, consultants and the restaurateur. Load management, equipment and appliance selection options were calculated to meet the needs of multiple restaurant concepts, so that a precise annual restaurant energy budget could be established for the final space. This part of the Energy Petal requirements for ILFI certification was so challenging that an alternative Water Petal analysis was completed to determine if the



8.

Project in numbers

- **2017-18:** design began
- **2024:** phase one completed
- **17,500m²:** new facilities
- **1.27MWh:** projected PV array generation annually
- **100%:** irrigation needs offset
- **757,000 litres:** rainwater cistern
- **+4m:** design flood elevation for Plant Research Center

design should shift to an on-site net zero water treatment strategy. The redesign of the restaurant space and optimisation of the parking roof PV system ultimately found the ideal solution to meet the energy requirements.

Originally designed as a conventional precast concrete structure, the team reconfigured it using post-tensioned concrete, reducing material quantities while creating a lighter and more open feel. To reduce the visual impact on the adjacent properties and integrate better into the scale of the neighbourhood, the building was reduced in height from five to three storeys, with the exterior columns repositioned away from the perimeter with balanced cantilever spans enabling a thinner floor plate profile. Planters integrated into the façade and roof allow vegetation to climb and soften the building's profile, connecting it visually to the surrounding landscape, while also reducing heat gain.

To address community concerns about noise, Arup's acoustics specialists advised on layout changes, relocating the restaurant to the ground floor and away from neighbouring homes. The firm also designed mechanical systems to discreetly integrate into the garage and rooftop, with screening and acoustic strategies to minimise both visual and auditory impact. These adjustments, combined with refined ventilation and envelope strategies, helped the project meet both environmental and social performance goals.

The LEAF demonstrates how a building serving everyday functions, including parking, retail and dining, can work as a living part of an ecological system. Its success depended on a combination of technical precision, design adaptability and continued collaboration with the client and wider team.

Safeguarding scientific heritage

The Steinwachs Family Plant Research Center is the scientific heart of the Marie Selby Botanical Gardens. It houses laboratories, research spaces and a world-class herbarium, a collection that preserves and studies thousands of plant specimens, and has one of the world's most significant orchid and epiphyte seed repositories.

Arup designed for both precision and protection. The team worked with Overland to create a building that could meet strict environmental control requirements while withstanding the increasing threats posed by hurricanes and flooding. The structure, formed from hollow-core precast concrete planks on a steel frame, elevates the most critical collections and mechanical systems to the second floor, providing an additional 4m of flood protection. The lower level incorporates a combination of wet and dry floodproofing strategies, ensuring that the facility can continue operating even in extreme weather conditions.

For Arup's engineers, the challenge was to combine the climate resilience required in Florida's gulf coast with the stability and control essential for scientific research. The mechanical, electrical and public health systems were designed to maintain highly stable temperature and humidity levels for the seed and specimen collections. To safeguard against power outages during storms, backup battery power connected to the PV array was provided to meet 10% of total demand, in alignment with ILFI requirements. Additionally, a propane generator that provides backup power to the herbarium functions received a project-specific combustion exemption from ILFI for its lower-carbon-intensity fuel in acknowledgement of the protection of these critical resources. This is crucial because the research centre houses irreplaceable scientific resources, which means any interruptions to power, climate control and security or IT could jeopardise living collections, preserved specimens and research continuity.

The herbarium was a unique challenge. The team had to understand how it operated and what its research functions demanded, and then design spaces that met those needs efficiently. The result was a flexible, durable environment that supports both research and education. It also lets visitors see aspects of the scientific process usually hidden from public view.

Each laboratory instrument, climate-controlled cabinet and specimen freezer was documented and integrated into the energy calculations for the site. This detailed coordination supported the Selby Gardens' net-positive goals while ensuring that research integrity and resilience were not compromised. In balancing energy performance with scientific precision, the Plant Research Center proves that sustainable design can enhance, rather than constrain, complex technical facilities.

Building through adversity

Delivering a project of this scale and ambition required persistence and flexibility. The design and construction teams faced an exceptional combination of challenges, from extreme weather and the COVID-19 pandemic to supply-chain delays and budget pressures.

9.

Hurricane resilience was a defining theme throughout, with one major storm hitting the region during construction which impacted some of the suppliers on the project and the Category 5 Hurricane Milton striking a few months after the new facilities opened. While many nearby buildings sustained heavy damage, the newly completed Selby Gardens structures remained intact. The only impact was the loss of approximately 30% of the rooftop PV panels, which were rapidly replaced. The herbarium, labs and restaurant remained unscathed, validating all the resilience measures built into the project.

The pandemic added complexity. Site work slowed as travel and supply restrictions affected both materials and workforce availability. Arup and its partners adjusted sequencing and procurement strategies to maintain progress, while digital coordination became essential for design and client reviews.

Sarasota's distance from major construction hubs also shaped the project. Specialist contractor and material availability was limited compared with larger urban centres. The Arup team worked closely with the main contractor to understand what could be built locally and to adapt designs accordingly. For example, the decision to use post-tensioned concrete for the LEAF facility came about through early collaboration with local subcontractors and ensured constructability while maintaining the project's sustainability goals.

Budget control was another recurring challenge. Rising material costs during

10.

8, 9: The Family Plant Research Center houses laboratories, research spaces and a world-class herbarium

10: Selby Gardens is home to one of the world's most significant orchid and epiphyte seed repositories

11.

11: The LEAF is topped by a 877kW DC rooftop solar PV array

12: Marie Selby Botanical Gardens is one of the world's first botanical garden complexes to be energy net positive

13: The energy return from the PV array is expected to generate 5% more power on an annual basis than Selby Gardens consumes

the pandemic made coordination among the design, engineering and client teams crucial. Design flexibility meant the project stayed on track without compromising its environmental targets or architectural quality.

Despite these challenges, the team maintained a consistent vision: to deliver a resilient and inclusive campus that could serve both its scientific community and the wider public. The experience strengthened cooperation across disciplines and reinforced the value of early contractor engagement, principles that continue to inform Arup's approach to complex, climate-sensitive projects worldwide.

Collaboration and craft

The project's success lay in how well the teams combined expertise. Arup's structural, mechanical, electrical and sustainability specialists, working in collaboration with the wider design team, developed solutions in parallel rather than in sequence, allowing performance, cost and design intent to be considered together. This collaborative method reduced inefficiencies and ensured that the facilities, particularly the LEAF and the Plant Research Center, functioned as integrated systems rather than standalone buildings.

Equally important was the partnership with Selby Gardens' operational and scientific teams. Their detailed understanding of research processes, maintenance requirements and visitor experience informed many design decisions, from laboratory layouts to public circulation. This exchange of knowledge helped create spaces that are technically robust and straightforward to manage.

The process demonstrated how collaboration was a design tool in itself. It shaped outcomes that are efficient, resilient and responsive to real-world conditions. By integrating architecture, engineering and operations from the start, the team delivered a result that embodies Selby Gardens' mission: to work in harmony with nature through thoughtful design and collective effort.

12.

Lessons for future botanical gardens

The experience gained at the Marie Selby Botanical Gardens offers insight into how net-positive and climate-resilient design can be achieved. One of the project's main lessons is the importance of early and continuous alignment between sustainability goals, client operations and technical delivery. Achieving a regenerative campus required advanced engineering and full commitment from Selby Gardens' management, researchers and restaurant operators. The need to review each system for energy use, from kitchen appliances to scientific equipment, reinforced that performance targets depend as much on human behaviour as on technology.

Arup's multidisciplinary involvement underscored the advantage of integrated design. Coordinating structural, mechanical, electrical and sustainability strategies from the outset avoided duplication and reduced costs, while supporting Energy, Place and Beauty Petal certification through the Living Building Challenge of the ILFI. The project has completed the Energy Petal Ready Audit and is currently monitoring performance for the 12-month occupancy period to confirm annual net zero energy compliance.

Finally, the project reinforced the need for adaptability in regions facing climate uncertainty. Elevating the herbarium, designing flood-resistant lower levels and testing systems through major hurricanes have created a framework that other cultural and research institutions can follow.

The Selby Gardens redevelopment demonstrates that environmental responsibility can be embedded into every stage of design and operation. Its approach, linking sustainability, resilience and public engagement, sets a precedent for future botanical gardens and similar institutions seeking to act as living examples of ecological design in action. The structural design was driven by nature – incorporating resilience to hurricanes – but with an expressive approach to the structure that reflected nature and the setting of the gardens on Florida's Sarasota Bay.

13.

Beyond the technical achievements, the redevelopment provides a model for how mission-driven institutions can use infrastructure to advance their environmental objectives. Selby Gardens' new facilities support scientific work, improve visitor access and reduce long-term operational costs, showing that sustainability can strengthen both purpose and performance.

As one of the first botanical gardens in the world to operate as a net-positive energy campus, Selby Gardens sets a benchmark for the future. Its success reflects not only the technology behind it, but also the shared commitment that made it possible.

Authors

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Project credits

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Landscape architect Olin Studios
Civil engineer Kimley-Horn
PV array designer and installer One80 Solar
Main contractor Willis Smith Construction
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A surge of innovation

The trial of two low-carbon concrete mixes in Hexham's flood defences contributed to updated British Standards, while bold decision-making on the design saw further carbon and cost savings

Authors Donald Daly, Neville Long, Michael Sataya

When Storm Desmond hit the UK in December 2015, it quickly exposed the vulnerability of northern towns and communities to climate-related extreme weather. Some 43,000 homes across north-east England were left without electricity, while blocked roads, collapsed bridges and landslides stranded thousands of residents.

Lying just downstream of the confluence of the two branches of the River Tyne, the historic Northumbrian town of Hexham found itself particularly prone. The storm caused the Tyne to reach a peak flow of 1,730m^3 per second – the highest rate it has ever recorded. In Hexham, two industrial estates on opposite sides of the river were flooded, with properties including businesses, critical local services and housing overwhelmed, as there were only minimal flood defences to protect them.

The £6.5m Hexham Flood Alleviation Scheme (FAS), which was completed in September 2023, is intended to reduce the risk of flooding during a similar storm event. A collaborative effort led by the Environment Agency, designer Arup and contractor BAM Nuttall, the FAS comprises 300m of reinforced-concrete flood walls and raised embankments on both sides of the river. According to modelling by the Environment Agency, it cuts the likelihood of flooding in any given year in half.

While this will offer vital protection to Hexham's regionally important commercial activities, the FAS's impact could be felt more widely. Between the initial proposal and the final design, the scheme's whole-life carbon emissions were reduced by 49%. Detailed analyses of flood risk, cost and carbon impacts allowed the team to design out a 100m flood wall, and provided the commercial case for the purchase of a critical part of the site – an unusual step for the Environment Agency, but one that led to a more material-efficient solution.

The decision with perhaps the most far-reaching impact was the trial of two low-carbon concrete mixes, neither of which were covered by British Standards at the time of construction. The two products, supplied by Tarmac, reduced carbon emissions by 64% and 70%, compared with a 100% Portland cement (CEM I) mix. This work provided valuable data for the latest update to the British Standard for concrete specification, BS 8500, as well as laying down a marker for future infrastructure projects. With the UK Government recently pledging to invest £7.9bn in flood defences over the next decade, such innovations could have a significant bearing on the carbon cost of the UK's climate mitigation efforts.

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2.

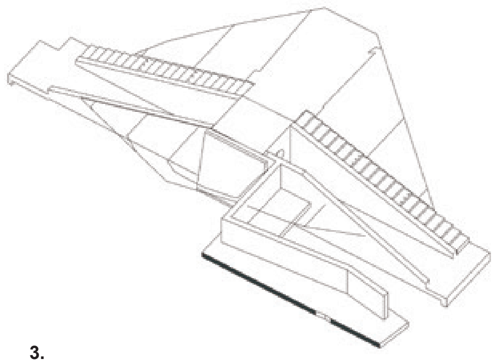
1: The flood alleviation scheme was a collaborative effort led by the Environment Agency, designer Arup and contractor BAM Nuttall

2: The Bridge End Industrial Estate housed a critical electricity substation

After the flood

The Environment Agency's modelling after Storm Desmond showed that the Tyne Mills Industrial Estate, which includes a sewage treatment works and pumping station, along with a local council depot, had a 2% chance of flooding in any given year. On the opposite, north bank of the Tyne, the Bridge End Industrial Estate had a lower 1.33% chance, but contained a critical electricity substation. The aim of the agency's £6.5m investment was to reduce the risk to 1% for both estates.

The initial proposal swiftly identified the need for reinforced-concrete flood defences on both banks, to the east of the heritage Grade II-listed Hexham Bridge. A 195m-long wall would protect the south side of the river, while a 245m-long wall would flank the north bank. The structures would range in height from 1m to 1.5m and would take the form of an inverted T shape, with a 300mm-thick vertical wall rising from a raft foundation 500mm below ground level.



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3: A high-level overspill is included in the Skinnersburn tributary trough to mitigate potential blockages

4: When the Tyne's water level rose during Storm Desmond, it backed up in the Skinnersburn tributary

5: Reinforced-concrete flood defences were constructed to the east of the heritage Grade II-listed Hexham Bridge

6: To test the concrete mixes, three 9m-long wall sections were built

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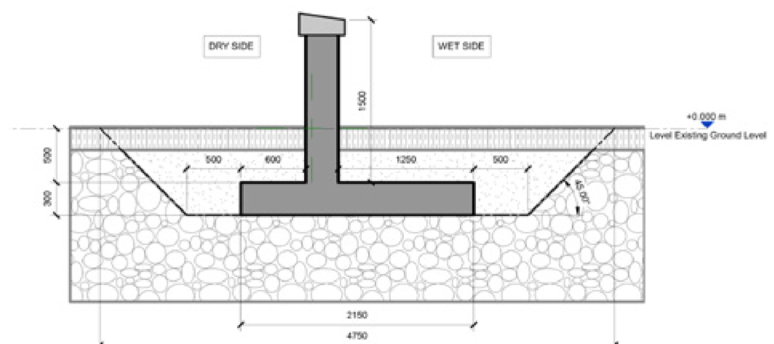

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Meanwhile, raised embankments would extend the defences to 300m on the south side and 370m on the north. Designed in accordance with Eurocode 7, these would slope at a gradient of 1V:3H and be topped with a 3m-wide crest. They would be constructed using cohesive engineering fill and compacted soil to a maximum height of 3.2m.

A further focus of attention was a tributary on the south bank, known as the Skinnersburn. When the Tyne's water level rose during Storm Desmond, it backed up in the Skinnersburn, further inundating the Tyne Mills estate, as well as a neighbouring cottage. The proposed remedy was an additional steel-sheet-piled flood defence, stretching for 100m along the tributary.

Change of approach

Arup was appointed as lead consultant for the design phase in 2019. This was an opportunity to optimise the scheme in line with the Environment Agency's carbon targets, as well as to implement the Project 13 principles that Arup helped to develop for the Institution of Civil Engineers. These aim to improve project outcomes in the infrastructure sector by moving away from a traditional transactional business model towards knowledge sharing throughout design and construction. The idea is that by developing long-term relationships between project owners, consultants and suppliers, this will lead to better decisions and more opportunities for value creation.

The team were quickly faced with a technical challenge arising from the original proposal. On the north bank, the previous consultant had proposed a route for the flood wall that threaded behind an existing building, very close to the electrical substation and the edge of the riverbank.

Following a ground investigation and initial geotechnical analysis, it became apparent that major engineering works would be required to the existing riverbank and revetment to support the flood wall, resulting in significant increased cost and carbon impact. In addition, hydraulic modelling of this alignment showed that it would increase flood risk to the residential property immediately upstream, necessitating additional flood defence to that property, as well as works adjacent to the heritage listed bridge, all impacting the setting of both the bridge and the property.

Through hydraulic modelling, and rigorous cost and carbon analysis, the team came up with a novel solution. The existing building had been an outlet store for a sports equipment company, but had lain vacant for several years. The Environment Agency proposed the demolition of the building. Arup developed the scheme with the client purchasing the building, enabling its demolition, which provided a simpler and safer solution. It mitigated the increased flood risk from the original solution, reducing construction risks and therefore overall costs. It was a win-win situation: the building owner could sell a depreciating asset and the alignment of the wall could be improved.

The electrical substation located within the demolished building had to be moved too, which required close collaboration at senior level between the Environment Agency and Northern Powergrid. A site was identified within the same plot of land, 30m from the original building, and an agreement was reached. Even factoring in demolition works and the construction of the new substation, the team was able to show that the streamlined programme and smaller quantities of concrete involved would reduce capital costs and carbon.

The Skinnersburn solution was also reviewed. The proposal for a sheet-steel flood defence required the removal of a number of mature trees. This would be damaging from an ecological perspective and would disfigure the garden of the neighbouring cottage, which was screened from the surrounding industrial estate by these trees. Construction works would have been disruptive to the residents and local businesses, and harmful to sensitive freshwater habitats.

Working with Northumbrian Water's modellers, the project team developed a more passive approach, eliminating the need for the 100m defensive wall without raising the flood risk. The new design involved building an embankment across the Skinnersburn valley and channelling the watercourse through a 2m-wide open concrete trough. A headwall was added centrally within the trough, with a 900mm-diameter opening and flap valve. Under a normal flow, the water coming down Skinnersburn would

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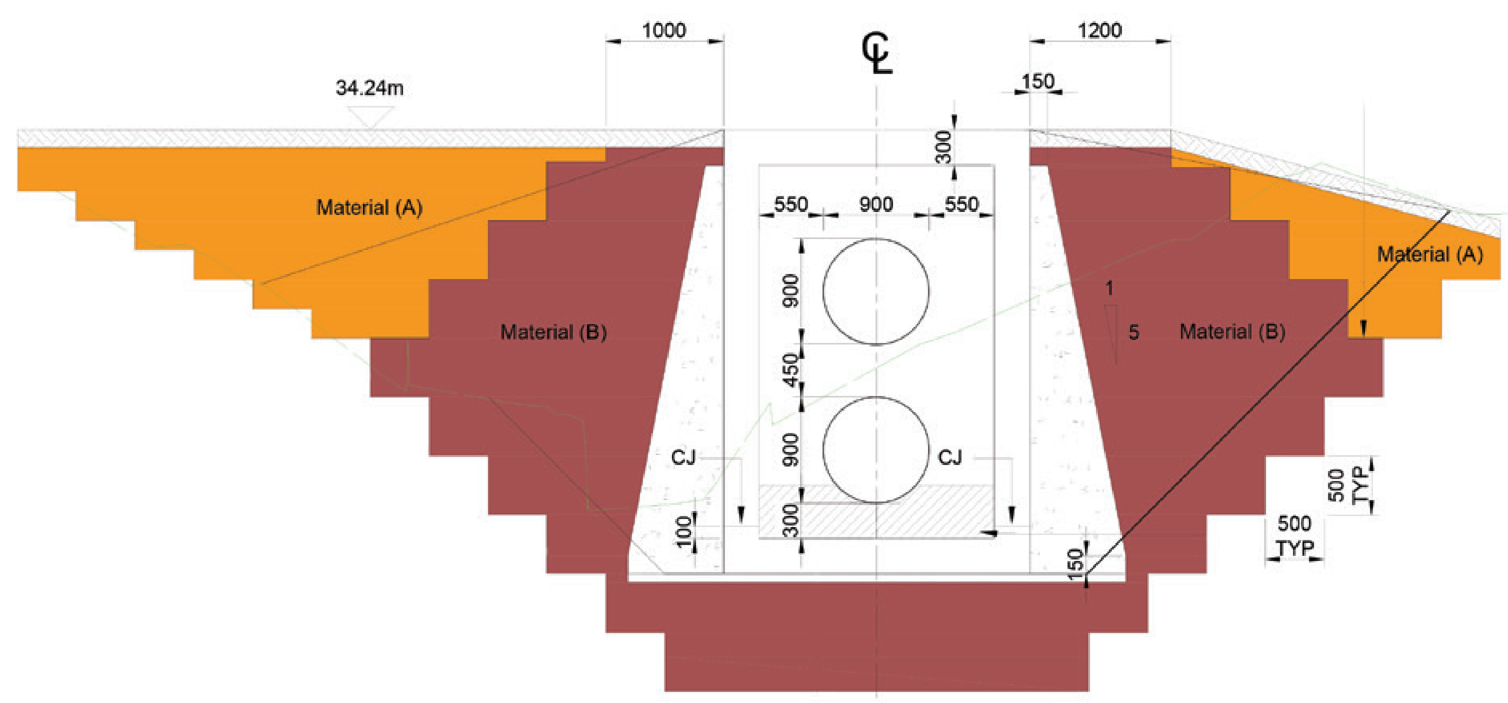
7: Two low-carbon concrete mixes were trialled as part of the flood defences at Hexham

8: The relocated sub-station is protected by the new flood defences

9: The Skinnersburn defences include two 900mm-diameter openings and flap valves in the headwall



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pass through the flap valve. However, during a flood, the water surging up from the Tyne would push the flap closed, preventing it from travelling further upstream and thereby protecting the surrounding properties. A high-level overspill is also provided to mitigate potential blockages.


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Low-carbon concrete firsts

The construction of a flood defence system inevitably involves concrete, but the Hexham FAS designers sought to optimise its use wherever possible. The walls were rationalised to a set of typical panel types between 0.75m and 2m in height. This approach allowed for more standardised construction, reducing waste and limiting the need for bespoke formwork and reinforcement. A lower-carbon concrete mix, designated CEM IIIA under BS 8500, was specified throughout. This replaces 50% of the cement – by far the most carbon-intensive ingredient of concrete – with ground-granulated blast-furnace slag (GGBS), a by-product of steel production. The result is a corresponding 50% reduction in the embodied carbon of the concrete compared with a standard CEM I mix.

However, the project team saw an opportunity to go further. In collaboration with concrete supplier Tarmac, the decision was taken to trial two lower-carbon mixes within the permanent works. The Net Zero Carbon for Infrastructure programme – a change initiative led by the Environment Agency to support the UK Government's national carbon reduction commitments – provided £88,000 of funding for the trial.

The two concrete mixes were based on innovative compositions of cementitious material, neither of which was covered by BS 8500. The first was an alkali-activated cementitious material (AACM) comprising over 90% GGBS and just 5% Portland cement. This works by adding a small amount of activating compound, such as an aluminate, to the mix – usually about 5% by volume of the binder. This changes the pH of the solution, kickstarting the hydration process of the GGBS. The AACM mix used at Hexham had a CO_2 equivalent of 100kg/m^3, 70% less than a standard CEM I concrete.

The second mix comprised 35% Portland cement, 20% limestone and 45% GGBS, resulting in a CO_2 equivalent of 119kg/m^3 – 64% lower than CEM I. The slightly higher embodied carbon of this mix reflects the increased level of Portland cement, although the addition of limestone powder is perhaps of greater significance. Because this has very low process emissions, the replacement of 20% of the CEM I is considered to reduce the concrete's embodied carbon by a corresponding 20%. With the production of steel being outsourced to other parts of the world, such blended – or ternary – cements that introduce a third cementitious material, reducing the demand for GGBS, may prove essential.

Put to the test

The section of flood wall chosen for the trial was on the site of the demolished sports outlet. This was partly because the defences in this area did not need to be particularly tall, measuring less than 1m from ground level. Another crucial factor was the land ownership – since the Environment Agency had acquired the site, it meant there would be no access issues for future inspection and monitoring.

10, 11 & 13: The Skinnersburn tributary is now channelled through a 2m-wide open concrete trough

12: During a flood event the water surging up from the Tyne pushes the flap closed, preventing the water from travelling further upstream and thereby protecting the surrounding properties


13.


14.


15.


16.

14: Data from the trials contributed to the 2023 revision to the British Standard for concrete specification

15: All the concrete was supplied locally by the same plant in Thrislington, County Durham

16: The section of flood wall chosen for the trial was on the site of the demolished sports outlet

To test the mixes, three 9m-long wall sections were built – one using the AACM, one using the limestone blend, and the other using the CEM IIIA mix specified on the rest of the project. All three were built to the same design, with a 1m-high wall and 21m-wide raft foundation, both 300mm thick. The concrete required a compressive strength of C32/40, as well as high levels of resistance to corrosion, chlorides and freeze-thaw action. Laboratory tests were undertaken in the weeks before the trial, leading to some minor adjustments to both mix designs. All the concrete was supplied locally, by the same plant in Thrislington, County Durham.

As neither of the new mixes were covered by BS 8500, the control section was vital. A robust testing regime was designed following guidelines in Publicly Available Specification (PAS) 8820, and this required close reference to a correctly specified benchmark. Slump and segregation tests were carried out on the freshly delivered mixes, while strength gain was tested on days 1, 3, 7, 28 and 56 after the concrete was poured. Other mechanical properties such as tensile strength and shrinkage were also measured as the concrete cured.

The performance of the new mixes proved impressive. Both met the scheme specification and achieved an A+ benchmark rating for embodied carbon. Tensile strength and shrinkage were at least as good as the reference concrete. Data from the trials contributed to the 2023 revision to BS 8500 – the ternary blend can now be specified under the designation CEM VI, with up to 20% of the Portland cement replaced by limestone.

AACMs still cannot be specified under BS 8500. The trials did, however, help to inform the recent publication of BSI Flex 350, which has succeeded PAS 8820 as the key guidance for developing test procedures for novel cements. The specific AACM used at Hexham is undergoing further development. Follow-up trials need to be undertaken to show that it can consistently meet the C32/40 strength class, particularly in cold temperatures. Its resistance to freeze-thaw was lower than the control mix at Hexham, although it showed greater resistance to chlorides.

Decarbonisation programme

Subsequently, Arup provided specialist technical advice to the Environmental Agency in developing a business case for the development of their major low-carbon technology

17: An aerial view of the concrete trough used along the Skinnersburn tributary

17.

upscaling programme. This involved identifying several novel low-carbon concrete technologies that could be sufficiently developed to become business as usual during the timeframe of this Decarbonisation Technology Accelerator (DTA) programme. This included, among others, the technologies trialled at Hexham.

Arup is leading one of the six elements of the programme – Novel/Ultra Low Carbon Concrete (Concrete 1) – and inputting into the Low Carbon Concrete (Concrete 2) element. The Concrete 1 element seeks to accelerate the adoption of several novel low-carbon concrete technologies, including calcined clays and high limestone filler content binders, as well as alternatives to steel reinforcement, such as basalt, nationally across the Environmental Agency's six regional hubs.

Beyond carbon

Other aspects of the Hexham FAS demonstrated the wider social value infrastructure projects can bring to a community. The project was delivered with a 92% local workforce, while 25% of supplier spending was with local businesses. The site team welcomed 10 education engagement visits, including more than 300 students. During the appraisal and design process, the team communicated extensively with landowners and businesses to understand their needs, particularly the importance of keeping the estates operational during construction.

Close collaboration during the design stage led to solutions that were less intrusive, more efficient and less disruptive to communities and habitats. The willingness to innovate on a live project has helped pave the way for a future less reliant on GGBS and makes the Hexham FAS a template for reducing the embodied carbon of essential infrastructure.

The scale of upgrades needed to UK flood defences over the coming decades is immense. The Environment Agency predicts that, by 2050, one in four residential and business properties will be at risk of flooding. The work at Hexham suggests there could be a way to protect these communities without increasing our dependence on cement.

Authors

Donald Daly was the Project Manager. He is an Associate Director in the Newcastle office.

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Michael Sataya provided special materials expertise on the low-carbon concrete elements of the project. He is a Senior Engineer in the Nottingham office.

Project credits

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Concrete supplier Tarmac
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Image credits

1, 3-7, 9, 14, 15: Arup
2, 8, 10-13, 16, 17: BAM Nuttall

1.

1: Ireland House Tokyo houses the Irish Embassy, the ambassador's residence and offices for state agencies

A landmark of cultural connection and design excellence

Innovative engineering solutions on a compact site deliver a new centre for Irish diplomacy, business and culture in Japan

Authors Junichiro Ito, Mitsuhiro Kanada, Rory McGowan, Niamh McKevitt, Shuichi Tamura

Ireland House Tokyo, commissioned in 2019 and opened in 2025, is a landmark centre for Ireland's diplomatic and cultural presence in Japan. Located in Tokyo's Shinjuku ward, it houses the Irish Embassy, the ambassador's residence, and offices for state agencies including Bord Bia, Enterprise Ireland and IDA Ireland. It is the latest such facility, with Ireland Houses now located in over 21 cities around the world, including New York, Shanghai and San Francisco. The Tokyo building features an acoustically designed performance space that doubles as an exhibition area, as well as a business/conference facility, a cultural resource hub and the Lafcadio Hearn library – named after the Irish writer who at the turn of the 20th century was one of the first Western observers of the Japanese way of life. His works are still regarded as classics in Japan.

Following an international design competition conducted by the Department of Foreign Affairs and Trade, and the Royal Institute of the Architects of Ireland, architectural practice Henry J Lyons was appointed as the design team lead. They assembled a multidisciplinary project team, including Integrated Design Associates with Taro Ashihara Architects for local architectural expertise and Arup, who supported Henry J Lyons during the project competition, providing structural, mechanical, electrical and public health engineering design services.

The 2,700m² hybrid concrete and steel structure has two basement levels and five floors above and was designed to maximise the available footprint on a constrained urban site. The resulting stepped architectural form introduced geometrical complexity, and the integration of an innovative lateral stability system was required to meet Japan's highest seismic resilience standards. The design of the facility emphasises sustainability (attaining the highest rank from Japan's foremost sustainability benchmark assessment), resilience and security, bridging Irish and Japanese values while meeting the complex operational needs of a modern diplomatic mission.

Excellence through collaboration

Arup's contribution to the project was characterised by a collaborative approach, with the firm's team in Dublin leading the scheme design, working closely with colleagues in Tokyo to ensure that every proposal met local codes and regulatory standards. This early and integrated approach laid the groundwork for a smooth progression into the detailed design phase, during which both offices jointly coordinated complex components before the local Arup team in Tokyo assumed primary responsibility for producing construction documentation and overseeing on-site delivery.

By integrating global expertise with local knowledge, the firm ensured that the project's vision remained consistent and technical excellence was maintained throughout every stage. The design was shaped by the fusion of advanced seismic engineering, sustainability principles and meticulous detailing, all executed to the highest standards of craftsmanship. This holistic and integrated approach enabled the firm to support the client through complex decision-making, make efficient use of materials, and deliver solutions that were precisely crafted to address the project's unique and challenging requirements.

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2: The engineering design was a collaboration between Arup's offices in Dublin and Tokyo

3: The design maximises the available footprint on a constrained urban site with two basement levels and five floors above ground

Structural ingenuity

Located in one of the world's most seismically active regions, the building required a structural solution capable of withstanding significant lateral forces. An additional constraint was the requirement to adhere to the local 'sun-shadow rule', based on the principle of 'Nisshō-ken' (the 'right to sunshine'). This regulation imposes restrictions on building height and form in designated areas in order to ensure that adjacent properties retain sufficient natural daylight. As a result, the design produced an inherently asymmetric building, a configuration that posed significant challenges when it came to addressing the seismic force requirements.

Given this asymmetry, the structural team prioritised early collaboration with the client to ensure clarity around Japan's seismic design requirements and regulatory standards. This close partnership enabled well-informed decision-making, leading to the adoption of a robust, code-compliant concrete wall system. The walls were strategically designed to redress the eccentricity between the building's centre of mass and centre of stiffness, a critical consideration in seismic engineering design.

At the lower levels of the building, which house the public spaces on level -1 and building plant areas on level -2, and where there is a greater requirement for servicing, a strategy of recessing the concrete floor slab into the depth of the web of the structural steel beams was adopted. This provides a deeper and more flexible zone to run the building services below the beams.

Higher up the building, the overall buildup allowed from ceiling to finished floor overhead was reduced. Coupled with a reduced requirement for large ducts to be accommodated through the structural elements, this enabled a traditional slab support arrangement with deeper support beams, allowing services to be routed through openings in the web of the beams. To achieve a clear and column-free event space at ground floor, two 12m-long single-storey deep steel Vierendeel trusses were incorporated into the design, spanning the office space above and over the width of the double-height event space below.

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4: The building services elements were designed to deliver a sustainable, energy-efficient and environmentally friendly facility

5: Fair-faced, board-marked finishes were used for the concrete throughout the building

Innovative detailing and hybrid solutions

At the heart of the building is the 'outrigger lantern' – a central lightwell demanding both strong seismic performance and refined architectural detailing. Each corner features bespoke 1,000mm x 1,000mm cruciform concrete columns, their unique shape chosen to reduce visual mass. By separating the flanges visually, the columns appear slimmer, which enhances the sense of opening within the lantern.

Internally, the columns feature 100mm-thick steel plate reinforcement designed to resist the substantial tension forces that can occur during seismic events. Specially developed, discreet steel connections directly link the lantern's steel beams to these embedded plates within the cruciform concrete columns. This carefully engineered assembly ensures the lantern is securely tied together, resulting in a system that offers both exceptional stability and a visually light appearance.

Although the steel elements within the lantern structure were primarily responsible for resisting seismic loads, a significant technical challenge emerged due to the discontinuity of walls in one orthogonal direction of the building. This was compounded by architectural constraints and the sun-shadow rule. In response, two reinforced-concrete 'outrigger walls', varying in thickness from 400mm to 600mm, were strategically introduced to strengthen the lantern,

6.

6: The inherent thermal mass of the concrete walls absorbs excess warmth during the day, releasing it slowly as temperatures drop, passively moderating indoor conditions

7: Airflow is carefully managed in the double-height event space that is used for various diplomatic events

providing essential lateral stability. Rather than extending the full height of the building, these walls step back at intervals and were carefully detailed to allow for doorways and circulation.

Aesthetic achievement

An innovative approach was used in the design and construction of the concrete perimeter walls, which function both as the primary structure and the building's external façade. Unlike traditional cavity wall construction, this approach eliminates superfluous layers by using the concrete walls themselves as the envelope, substantially reducing overall material consumption without sacrificing either performance or aesthetic quality. With no external cladding to mask flaws, every exposed surface demanded exceptional precision and craftsmanship. This approach resonates deeply with Japanese architectural principles, which celebrate exposed concrete for its authenticity, durability and expressive character.

Fair-faced, board-marked finishes were used throughout the building, with the exposed concrete not only providing a durable and low-maintenance finish but also creating a sense of solidity and permanence, befitting of the building's diplomatic function. Despite the robust nature of the material, the architectural feel of the finished building is warm and inviting. Beyond its aesthetic contribution, the concrete structure is central to the building's environmental efficiency. Its inherent thermal mass absorbs excess warmth during the day, releasing it slowly as temperatures drop, passively moderating indoor conditions. This reduces the need for mechanical heating and cooling.

Sustainability was a foundational consideration in specifying and utilising concrete for the structure, despite the significant volumes necessitated by the project's structural requirements. From the outset, it was acknowledged that compliance with seismic standards required substantial reinforced-concrete walls and other robust structural elements – critical for both safety and performance. Nevertheless, every effort was made to maximise sustainability in the selection and application of concrete wherever feasible. For the two basement levels, founded on piled foundations and ground beams, a concrete mix containing a minimum of 30% Portland blast-furnace cement was specified for the walls and slabs. This choice not only significantly reduced the structure's embodied carbon but also enhanced its durability and long-term performance. Conversely, for the above-ground areas – where achieving the concrete finish was critical, the use of blast-furnace cement was limited to preserve the visual integrity of the exposed concrete.

Energy-efficient services

The building services elements were designed to deliver a sustainable, energy-efficient and environmentally friendly facility, with the strategy focusing on reducing energy demand, maximising energy efficiency and incorporating on-site low-carbon strategies.

Across the rooftop, 18.4kW of solar photovoltaic (PV) panels generate clean electricity for daily use. Rainwater is collected and temporarily stored in an underground tank – an approach that helps ease local flooding risk – with a portion of this stored water filtered and reused for toilet flushing.

Ventilation is handled by a total heat exchanger that recovers thermal energy, while CO_2 sensors regulate the intake of fresh air so that only what is needed is supplied. When outdoor conditions are ideal, an indicator light informs occupants that natural ventilation is possible by opening a window.

Arup developed the overall sustainability strategy by taking into account both technical and visual requirements, as well as the distinct building traditions found in Ireland and Japan. To realise the sustainability objectives, a thoughtful adaptation to these differing priorities was required, ensuring an approach that was aligned with local expectations and adhered to international best practices. The success of this approach can be seen in the awarding of the CASBEE S green building certification – the highest rank from Japan's foremost sustainability benchmark assessment.

Comfort

Central to the building's design is comfort. A variable refrigerant flow air-conditioning system allows each room to be controlled individually, giving occupants the flexibility to adjust their environments as needed. The fourth-floor residential area also features underfloor heating for added warmth. In the double-height event space, airflow is carefully managed. Conditioned air is gently supplied from above and returned through narrow openings near the floor, creating a quiet and even distribution without drafts. During winter, air can be directed from the floor on the dry-area side to counteract cold drafts from nearby glass surfaces.

A dedicated kitchen sits adjacent to the event area, and differential pressure sensors ensure that cooking odours stay confined to the kitchen, maintaining a pleasant environment for guests. In recognition that the building is located in a residential area, exhaust from the kitchen is released at the rooftop level through ducts, while noise-generating equipment is consolidated in a mechanical yard on the fourth-floor rooftop, with soundproof walls and silencers used to minimise noise as much as possible.

Emergency preparedness

The building is engineered to remain operational even during emergencies such as earthquakes and power outages. All equipment is anchored according to the highest seismic standards. In the event of a loss of power, an emergency generator can support essential functions for approximately three days, the rooftop PV panels can supply supplemental power and there is a dedicated storage battery that protects communication equipment from momentary power interruptions. To prepare for interruptions in municipal water supply, the building is equipped with both potable and reclaimed water tanks, ensuring that a minimum amount of water is always available.

7.

Diplomatic design delivery

The combined Arup team merged local insights with global expertise in the design of Ireland House Tokyo, in accordance with Japan's seismic performance and environmental performance criteria. In addition to meeting those technical demands, the overall project team has delivered a long-term asset for the Irish state to support complex diplomatic functions into the future. On 2 July 2025, the landmark diplomatic and cultural facility was officially opened by Ireland's Taoiseach (Prime Minister) Micheál Martin.

Authors

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Cost management Sato Facilities Consultants
Landscape designer Studio On Site
Acoustic engineer Nagata
Lighting design EQ2
Main contractor Taisei Corporation
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Image credits

1-2, 4, 6: Jonathan Savoie/Henry J Lyons
3, 5, 7: Arup

Reconnecting communities

Two new wharves in Sydney's historic Botany Bay are bringing communities back together, connecting with Aboriginal culture and respecting biodiversity

Authors Jamsheed Bhanja, David Dack, Rhys Lewis, Estelle Ouari

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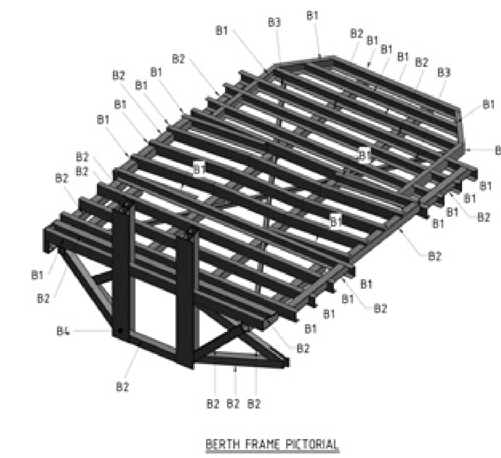

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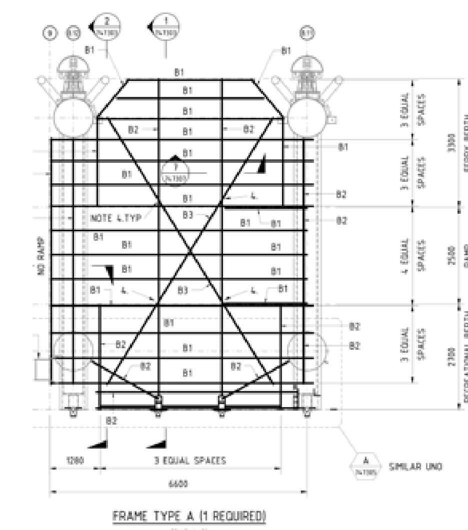

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1: The original wharves were built in the 1890s, with the latest construction replacing the wharves destroyed by a storm in 1974

2, 3: Arup conducted detailed numerical wave modelling to assess wave uplift forces acting on the underside of the wharf steelwork structures

Botany Bay, known as Kamay in the language of the local Aboriginal people, has a profound place in Australia's national story. It is a site of ecological richness, cultural memory and layered history that draws tourists year-round. It was here, in 1770, that the first documented encounter between Aboriginal peoples and European arrivals took place.

Wharves were constructed in the 1890s to connect the two peninsulas of Kamay, which is home to the Aboriginal Bidjigal and Gweagal people. But in 1974, they were destroyed by a storm, severing a historic connection across the bay. Fifty years later, the Kamay Wharves project has reinstated that link.

Arup partnered with Transport for NSW to deliver the project, which involved designing, developing and building new wharves at two sites in Botany Bay – Kurnell and La Perouse. Arup led the project from strategy through to delivery, working in partnership with local Aboriginal organisations and the wider community to create two new wharves that are robust, elegant and deeply rooted in place.

An interdisciplinary team of engineers, architects, maritime infrastructure experts and urban designers collaborated closely to deliver wharves designed for long-term resilience. The structures were engineered to withstand wave impact, corrosion, sea-level rise and broader climate-related risks. Architecturally and visually, the design sits within the coastal landscape. A minimal built footprint and use of single piles helped reduce ecological disturbance, while landscaped areas integrate places to sit, native vegetation, lookouts, and spaces for cultural gathering and reflection.

Environmental stewardship was central to the project. To protect sensitive marine ecosystems, a seagrass translocation and rehabilitation strategy was developed in partnership with the University of New South Wales (UNSW), the Gamay Rangers (a local Aboriginal land and sea management group), Transport for NSW and other stakeholders. Before construction began at Kurnell, UNSW scientific divers carefully relocated around 13,000 shoots of *Posidonia australis*, an endangered seagrass, from within the wharf's footprint. Naturally detached fragments of seagrass were collected from nearby beaches by UNSW and the Gamay Rangers and replanted at dedicated rehabilitation sites. This replanting effort is part of a long-term programme that will continue for up to a decade, supported by ongoing ecological monitoring.

The programme has been in place since June 2023, with early signs of success – over 400m^2 of *Posidonia* meadow have been restored, including an additional 100m^2 beyond the original project footprint. The insights gained from this initiative are already informing future *Posidonia* restoration efforts nationally. This is a pioneer project, both locally and nationally, with nothing of its scale previously attempted.

Embedding Indigenous knowledge

The Kamay Wharves project was committed to Indigenous engagement from the outset. For the local communities, Kamay is both a location and a living cultural landscape. The aim was to design infrastructure that is not only functional, but honours Indigenous identity, stories and connection to place. Transport for NSW and Arup therefore made connection with Country a central principle in the design and delivery of the new wharves. This approach recognises, respects and incorporates the relationship of Aboriginal and Torres Strait Islander people with their ancestral lands and waters. It ensures that infrastructure and built environments reflect Indigenous cultural values, knowledge systems and custodianship. This principle influenced everything from community consultation to the architecture and artwork of the wharves.

Arup engaged directly with the local First Nations communities to understand what they wanted from the project, and how their cultural practices, values and history could shape the design process. Importantly, this was not just consultation – it was active participation. Working alongside a Supply Nation-registered Aboriginal engagement consultancy and a local Aboriginal advisor, Arup's team facilitated ongoing, place-based engagement with the La Perouse Local Aboriginal Land Council (LPLALC) and the broader Aboriginal community.

The group appointed Marcia Ella-Duncan OAM as strategic advisor. Ella-Duncan grew up in La Perouse and is a descendant of the Gandangara and Walbunja people. She has extensive public sector experience and played a pivotal role in fostering meaningful dialogue between the project team and community representatives. Her long-standing relationship with the

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LPLALC enabled early engagement in January 2020, just weeks after the project began. This early communication shaped the trajectory of the project, opening links to other key community organisations, including the La Perouse Aboriginal Community Alliance and the La Perouse Government Interagency Group.

As trust deepened, additional Indigenous-led organisations were engaged. The Gujaga Foundation, a not-for-profit focused on language, culture and research within the La Perouse Aboriginal community, collaborated closely with Arup's design team. Indigenous artists Jordan Ardler and Shane Youngberry, who have natural family ties to both sites, contributed to the identity of each wharf, with their work integrated into structural and landscape elements. Arup also exceeded the NSW Government's Aboriginal Participation in Construction stretch target, achieving 3.3% participation across the contract value (more than double the expectation). This included the appointment of four Aboriginal-owned or community-controlled organisations and the direct involvement of Aboriginal staff.

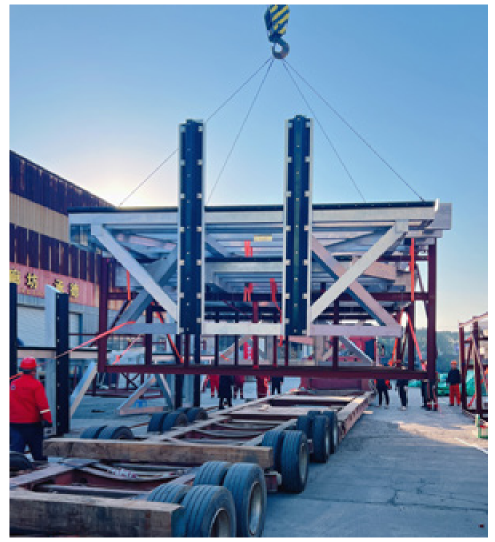
Beyond design, this process reinforced Transport for NSW's Reconciliation Action Plan objectives and delivered economic and social value to local Aboriginal communities. For Arup, it set a benchmark for how infrastructure projects can incorporate First Nations perspectives in practical and meaningful ways.

Placemaking by design

The wharves were designed not only as transport infrastructure, but as places – accessible, resilient and welcoming. Each site reflects the distinct character of its community and surroundings, while contributing to a shared identity for the broader Botany Bay area.

At La Perouse, the new wharf extends 104m into the bay with a distinctive dogleg design. Kurnell Wharf is longer, stretching 224m seaward, with a strong linear form that responds to wave exposure and marine conditions. Both feature overwater shelters with integrated Aboriginal artworks, shaded seating, interpretive elements and soft landscape treatments. Interpretation is built into the wharves through large Aboriginal artworks integrated into the shelter ceilings and cultural motifs sandblasted into the concrete walking surfaces. These are paired with inlaid pavers and interpretive signage to tell local stories on site. Minimal built form, single piles and floating berths reduce the visual and ecological impact.

Lighting design also played a critical role. The team used Arup's Nighttime Vulnerability Assessment tool to understand perceptions of safety, particularly among women and girls, on an adjacent walking path. At night, bollard lights along the 400m-long Monument Track walking path shift from a warm amber – less attractive to insects and less disruptive to wildlife – to a brighter tone when movement is detected, helping people feel safer and conserving energy. As a result of daylight studies and careful detailing, sunlight filters through perforated shelter roofs, enhancing visibility of the artworks.



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Engineering for resilience and ecology

Located at the exposed heads of Botany Bay, the wharf sites at Kurnell and La Perouse presented significant engineering challenges. Harsh wave environments, shallow bedrock, climate risks and sensitive marine ecosystems all shaped the design approach.

One of the early challenges Arup faced was the lack of any existing geotechnical information for the site. The team undertook a complex offshore investigation from scratch, with Arup leading, working with a subconsultant who carried out drilling to collect core samples from the seabed.

Arup conducted boreholes on each side of the bay at a limited number of locations. Even with that small sample set, the team found significant variation in the ground conditions. This inconsistency made the design process particularly challenging, as the designers had to account for a wide range of subsurface scenarios and develop a structural solution that could accommodate unpredictable conditions.

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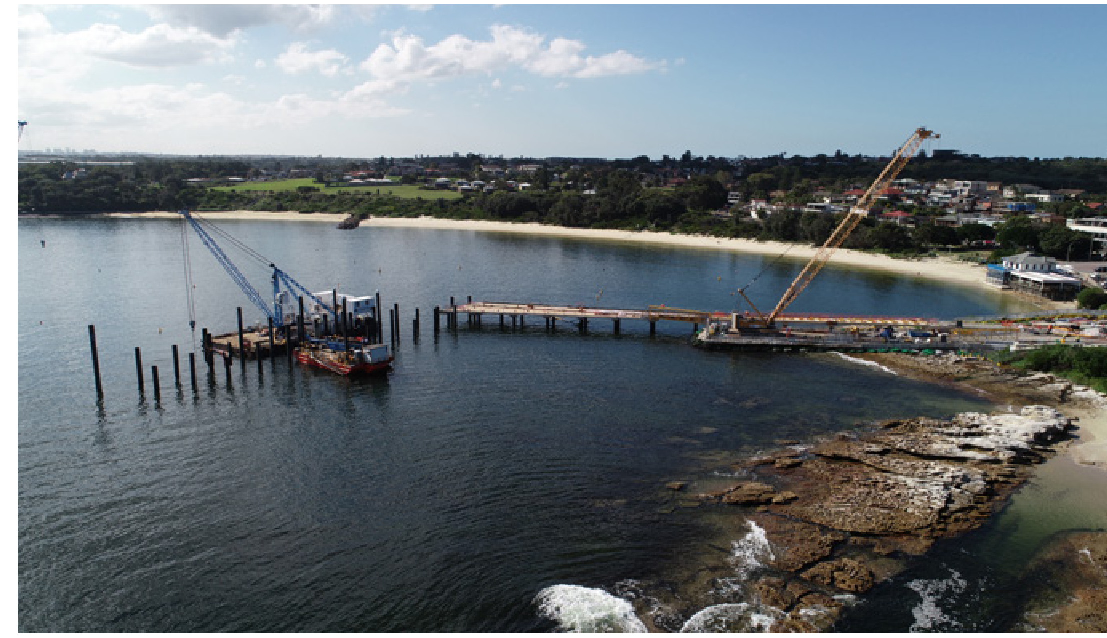
4: The wharves feature overwater shelters with integrated Aboriginal artworks and perforated roofs that allow sunlight to filter through

La Perouse was more challenging geotechnically. The ground conditions there were highly variable, and the site is exposed to large ocean swells. Arup explored using a hydraulic platform that could maintain a vertical clearance from the water, automatically moving up and down through the use of sensors, but it was costly and not user-friendly for other groups like fishermen and recreational users. A floating platform was discounted due to the high wave climate at the sites. The team opted instead for a fixed platform.

The design team carefully analysed vessel motion responses both at berth and in transit to inform the structural form of the wharves. Arup conducted detailed numerical wave modelling to assess wave uplift forces acting on the underside of the structures in these high-energy environments. Shallow rock levels and significant wave loading meant traditional piling methods were insufficient.

Instead, the design uses rock-socketed steel piles to handle wave uplift forces and provide enough tensile capacity in the shallow bedrock conditions. The wharves are built to endure rising sea levels, strong wave energy and corrosion, with hard-wearing materials that minimise maintenance needs over time.

Environmental protection was a key priority throughout. The wharves were designed to minimise their footprint on the seafloor, avoiding unnecessary shading or dredging. However, some impacts to seagrass meadows – specifically the threatened seagrass species *Posidonia australis* – were unavoidable. In response, Arup led the development of a Marine Biodiversity Offset Strategy (MBOS), the first of its kind in New South Wales. The strategy sets out how Transport for NSW will



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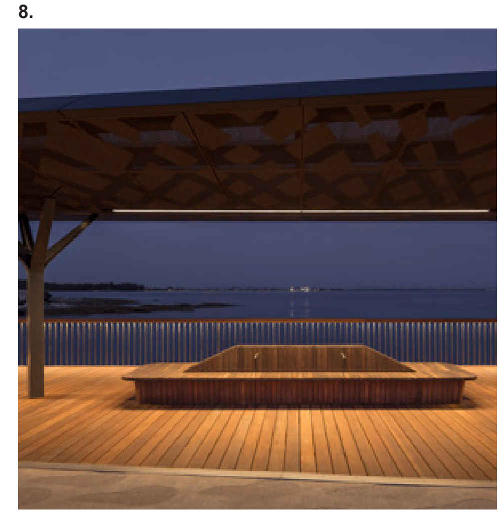

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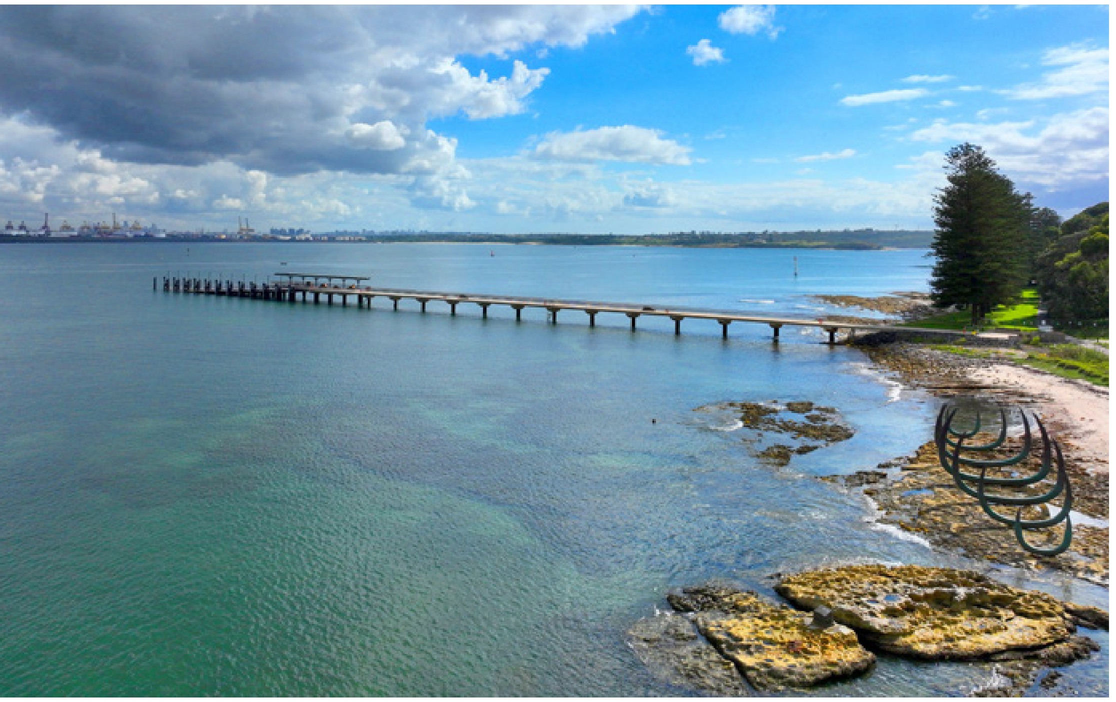
5, 6: The structures were engineered to withstand wave impact, corrosion, sea-level rise and broader climate-related risks

7: At La Perouse, rock-socketed steel piles were designed for wave uplift and to provide the required tensile capacity in the shallow bedrock conditions

8: Single piles were used to reduce ecological disturbance to the coastal environment

9: Material choices focused on durability, low maintenance and reduced environmental impact



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manage and mitigate the residual impacts of the project on marine ecology and biodiversity, to ensure no net marine biodiversity loss in Botany Bay as a result of the construction of the wharves.

The MBOS included a three-stage seagrass translocation and rehabilitation programme in partnership with UNSW's Centre for Marine Science and Innovation, the Gamay Rangers and Transport for NSW, as well as state and federal government agencies. Scientific divers relocated the seagrass shoots from the wharf footprint at Kurnell prior to construction and replanted detached fragments during construction and this will be done on an ongoing basis. Early

10: Kurnell Wharf stretches 224m seaward

11: Arup led the development of a Marine Biodiversity Offset Strategy which sets out how Transport for NSW will manage and mitigate the residual impacts of the project on marine ecology and biodiversity

12: Naturally detached fragments of seagrass were collected from nearby beaches and replanted at dedicated rehabilitation sites

13: The team selected warm amber lighting for the project to minimise disruption to wildlife

11.

12.

results are promising, and long-term monitoring is ongoing and will continue for up to 20 years.

The project also installed 60m^2 of 'seahorse hotels' – artificial structures designed to support the endangered *Hippocampus whitei* (White's Seahorse), which are present at the sites and inhabit the seagrass meadows. These modular metal frames attract marine growth over time, creating complex habitats that support biodiversity and encourage habitat connectivity. While the hotels initially function as artificial shelters, over time they become colonised by marine life and the corrosion of the metal framework gives way to organic growth, resulting in a new form of naturalised habitat ideal for the seahorses' long-term use.

This integrated ecological approach, underpinned by evidence and ongoing monitoring, demonstrates how infrastructure design can measurably align with biodiversity protection.

A whole-of-life project

Arup's role on the Kamay Wharves project spanned the entire lifecycle, from strategy and business case through to design, procurement and construction. This long-term involvement over five years allowed the team to ensure consistency, collaboration and quality from start to finish. The group brought together more than 30 disciplines, including architecture, maritime engineering, environmental science and other related fields. Key collaborators included PlanCom for community engagement, ConnellGriffin for procurement and WT Partnership for cost estimation.

A strong interdisciplinary culture was central to delivery. Engineers, urban designers, ecologists and engagement leads worked side by side to test solutions, anticipate risks and ensure design decisions aligned with both technical and community priorities. The wharves' simple forms conceal the depth of technical coordination needed to make them work, with a result that is functional, resilient and adaptable to future transport uses, including ferry services.

Sustainability in practice

Sustainability shaped every stage of the Kamay Wharves project – from material selection to community access and ecological integration. Material choices focused on durability, low maintenance and reduced environmental impact.

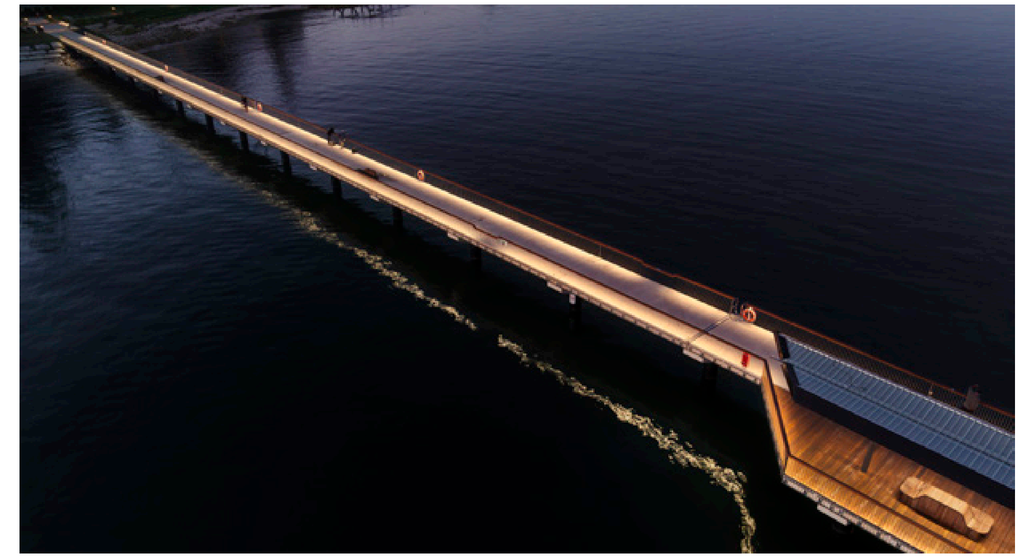
The wharves themselves are inclusive and welcoming spaces. Seating areas, interpretive signage, and accessible paths allow people of all ages and abilities to enjoy the coastal setting. These placemaking features make the wharves not just transport infrastructure, but public spaces that promote community interaction and cultural education.

Looking forward

The Kamay Wharves project shows what can be achieved when infrastructure is approached as a collaborative and integrated process. The wharves respect cultural heritage, enhance the environment and deliver enduring value to communities. A surprising additional bonus of the new wharves is seeing them used in different ways than originally intended. As ferry services have not started up yet, locals are using the wharves to dive into the water and as small swimming pools.

For Arup, Kamay is a clear example of total design in action, combining technical excellence, stakeholder insight, environmental stewardship and cultural awareness. It demonstrates the role infrastructure can play in reconciliation, not just by meeting targets, but by embedding Aboriginal perspectives throughout the design and delivery process.

As urban and coastal infrastructure become more culturally complex and exposed to more frequent climate change-related events, the Kamay Wharves provide a blueprint for what is possible: infrastructure that is strong, and respectful and relevant to the communities it serves.



13.

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Project credits

Client Transport for NSW

Partners Gamay Rangers, Gujaga Foundation, Jordan Ardler, Marcia Ella-Duncan, Shane Youngberry

Key collaborators
Community engagement PlanCom
Cost estimation WT Partnership
Procurement ConnellGriffin

Architecture, civil engineering, communications and community engagement, environmental consulting, geotechnics, lighting, maritime engineering, procurement, programme and project management, structural engineering, transport consulting Arup: Mick Agius, Victor Andrade, Hashan Aponsu, Jessica Athayde, Yostina Badawi, Sam Balian, Jamsheed Bhanja, Jonathan Bills, Frank Boyce, Russell Bunn, Peter Burnton, Filippo Caccamo, James Care, Tim Carr, Vincent Chan Kun Wa, Nancy Chen, Alice Choi, John Clayton, Andrew Crouch, David Dack, Donny Darmawan, Oliver Davey, Matt Davis, Evie Dryden, Hannah Drysdale, Heather Duff, Thomas Dunlop, Stefan Ellis, Lauren Elvidge, Laura Evelyn, Cameron Fairlie, Chris Fay, Elsa Feng, Georgia Flint, Marta Galindo Romero, Estela Oliari Garcez, Jacqui Gatehouse, Scott Gilbert, Scott Gleason, Lorrain Gong, Alan Grant, Suan Guo, Kurt Harris, Lachlan Hawthorn, Cameron Hough, Kavan Illangakoon, Matthew Inkster, Lorraine Jiang, Dane Johns, Lucy Johnson, Luke Johnstone, Jafar Kaabi, Ryan Kennedy, Reza Khoshkam, Elizabeth Kraska, Jessica Lam, Grace Lambeth, Jonathan Lambxin, Ida Larrazabal, Jacob Levy, Rhys Lewis, Peipei Liang, Bronte Linkhorn, Chang Liu, Adam Martin, Kirsten McDonald, Tess McGahan, Elisa McLennan, Andrea McPherson, Miles Miranda, Ross Newcombe, Cynthia Nguyen, Michael O'Connor, Estelle Ouari, Hillary Pan, Belinda Parker, Matt Pellow, Samyuktha Pillai, Tasnim Rahman, Charlie Sammoun, Jason Sanga, Christopher Serrano, Richard Sharp, Alice Smith, Luke Smith, Anurag Sobti, Matthew Stivala, Peter Suryadi, Mitchell Thompson, Andrew Turnbull-Miller, Mark van Uden, Elise Verrocchi, Philip Vimpani, Jo Walton-Hespe, Cloris Wang, Christine Watson, Andy Weir, Chani Wheeler, Thomas Whitehead, Ronnie Wong, Ruoshi Xu, Andrew Young, Darren Zhang, Ye Zhang, Cong-Ming Zhong, Damian Zhu.

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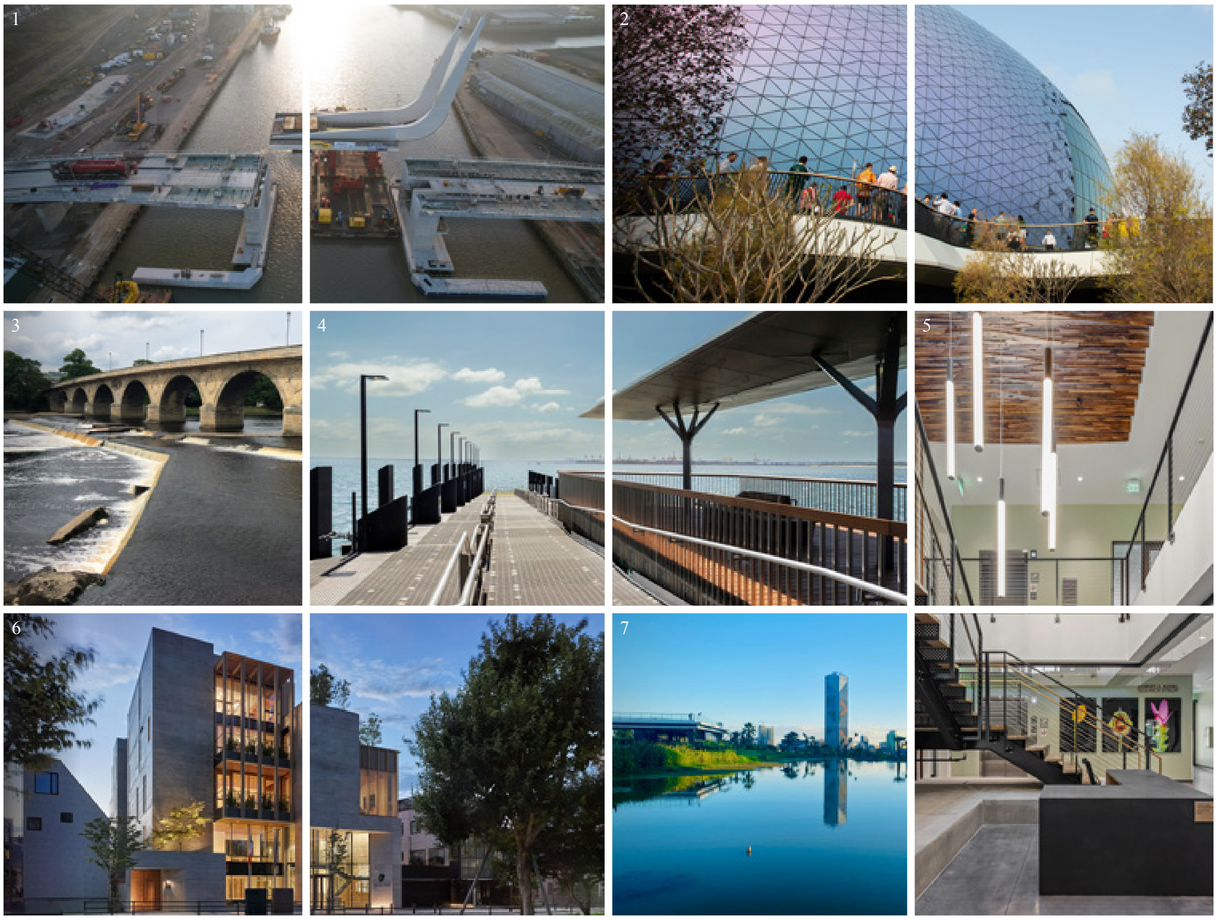

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