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The Arup Journal

Contents

1. Mountain Strolling Garden in Songdo IBD Central Park; view facing north towards one of the Korean Pavilions, with the four residential towers that form Block 125 within the city in the background.

Songdo IBD Central Park, Korea

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Central Park forms the focal point of Korea's Songdo International Business District, designed for sustainability, constructed on reclaimed land, and intended as a new business gateway to north-east Asia.

Introduction

In late 2001, the US developer Gale International retained Kohn Pedersen Fox Associates (KPF) to develop a masterplan for 650ha of land reclaimed from the Yellow Sea, 40km southwest of Seoul on the west coast of Korea, and not far from the new Incheon International Airport. In turn, KPF asked Arup to collaborate in developing sustainable ideas that could be incorporated into the masterplan. In December 2004 the masterplan was completed, presented, and accepted by the Incheon Free Economic Zone Authority (IFEZA).

The vision for Songdo IBD is to become a gateway to north-east Asia, an international city attracting global business, commerce, retail, and residential markets. Songdo IBD is being developed by New Songdo International City Development LLC (NSIC), a joint venture between Gale International and POSCO E&C.

3. 2005 architect's perspective of Central Park.

Offices, hotels, housing, and civic elements such as the Convention Center are included, as well as the Jack Nicklaus Golf Club Korea. In the last five years many Arup offices have contributed to the $30bn City's multidisciplinary engineering design, and this is the first of what is intended to be a series of *Arup Journal* articles on the key aspects.

Masterplanning Central Park

The 41ha Central Park (Figs 2-4) provides a multi-functional oasis for inhabitants of the tall residential and commercial structures that surround it. Arup's design scope included a major seawater canal, a three-level underground parking garage (2500 spaces), remediation strategy to provide a plantable landscape on a platform of sea-dredged soils, rainwater harvesting to provide sustainable irrigation supply, pavement analysis, drainage and utility design, and a robust lighting design for the Park.

2. Plan of Central Park.

The navigable seawater canal system (Korea's first), which supports a water taxi service, offers glimpses into the natural and man-made Park environments. In this it follows ancient city precedents — most notably that of Seoul. The placement of the canal system in the Park encourages use and views from various vantage points, and to help enable this a series of pedestrian bridges were designed to be focal points along the canal as well as unique destinations within the larger Park experience.

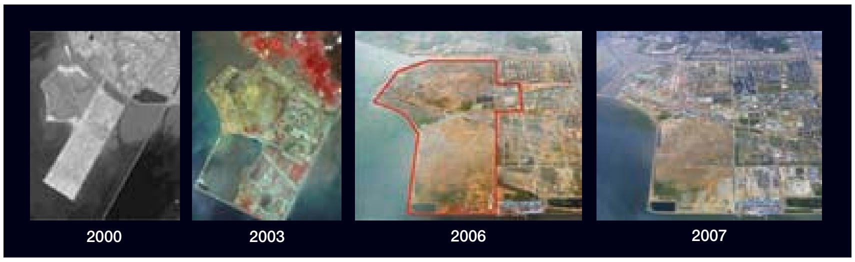
Throughout the Park, all the primary design features were developed to emphasise appreciation for the Korean peninsula, the various indigenous landscapes from mountain to shoreline being represented here at an intimate scale to serve as a reminder of the peninsula's natural beauty.

4. Central Park in the city context.

Table 1: Design responsibilities.

	Concept design	Schematic design	Design development	Contract administration	Construction drawings
US team	▓	▓	░	░	░
Local team		░	▓	▓	▓

5. Progressive reclamation of the land on which the city is being built.



Counterbalancing this naturalistic landscape, plazas and thoroughfares have been woven into the Park fabric to form connections between its buildings, which include cultural and government centres as well as a museum and aquarium. These pedestrian zones also serve as primary access routes across the Park and extend to schools east and west, and to the city's outlying areas beyond. A more intimate network of paths encourages exploration and passive recreation within the Park proper as visitors are encouraged to participate in the wonder of nature at close range. This unique combination of amenities and landscape make Central Park a lively destination and the heart of Songdo IBD. It was formally opened in August 2009.

Project framework

As with all the Songdo IBD projects with which Arup has been involved, the design process was split into five stages (Table 1).

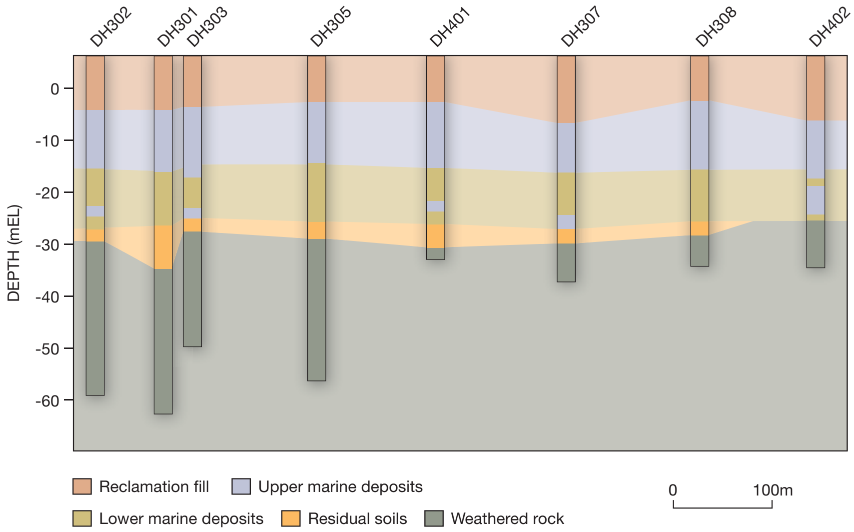
The US-based teams of development professionals, engineers and architects are responsible for the design from concept through to the end of design development. In the later stages of schematic design, and through design development, the companion local team of Korean architects and engineers carries out reviews to ensure that local code requirements are met. At the end of design development, responsibility passes to the local team to progress the design through to construction on site; the US team reviews construction drawings to ensure that the design intent is maintained.

For Central Park, the US team comprised Gale International, KPF architects and Arup. In the early stages, the landscape architecture was led by Towers Golde, but that role was shared between KPF and Arup from schematic design onwards. The local Korean team was led by Yooshin for architecture and engineering, with specialist support for the planting and ecological design of the canal system provided by local academic institutions.

The cost consultant, Davis Langdon & Seah Korea, was an integral part of the project team, with value engineering being addressed at each design milestone. Both capital and operational costs were considered, the former being born by the developer and the latter by local government bodies.

Ground conditions

Songdo IBD is being built on a platform of sea-dredged sands and silts hydraulically placed on the original seabed so as to raise the ground levels to between 6-7m above mean sea level. Satellite images of the Songdo area from 2000 to 2007 (Fig 5) illustrate the phased filling of the reclamation platform.



6. Typical geological section through Central Park.

A typical soil profile below the Central Park area comprises up to 10m of loose-to-medium-dense sands and silts which overlie the original seabed deposits of firm silts and clays; they become sandier and more dense below a depth of around 20m beneath ground level.

These silts, clays, and sands are produced by the marine and alluvial environment, and overlie the residual soils and highly weathered granitic bedrock encountered 30m below ground level. Groundwater levels are significantly affected by the seasons; the design groundwater level ranged from 1.5-4.0m below typical ground level.

Reclamation below the Central Park area was completed in 2003 and much of the settlement from consolidation of the original marine/alluvial deposits had finished before construction started in 2006. Further consolidation settlement due to the fill placement for the Park landscaping was accommodated in the engineering design. Across Songdo IBD, ongoing creep settlement of reclamation fill and the underlying marine deposits are anticipated to reach 0.5m over the next 50 years (Fig 6).

The canal design

Design team

The design of the canal system was a complex and unique process, with a range of issues requiring resolution using first principles or extensive research. To meet this challenge, Arup assembled a global team of specialists with skills in civil engineering, hydraulics and hydrology, maritime engineering, ecology, geotechnics, transport planning, and MEICA (mechanical, electrical, instrumentation, control and automation). Input came from more than 10 offices in the US, England, Scotland, Australia, Hong Kong, and the UAE.

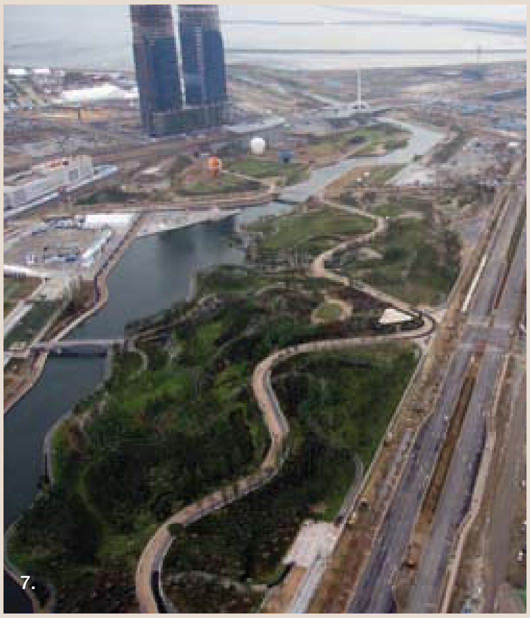
The canal design team was led from Arup's Northwest England office, which has been involved in the design of freshwater and seawater canals in East Asia, UK, and the Middle East. When client representatives came to see the team, they visited canals at Granton Harbour in Edinburgh and Salford Quays in Manchester, which helped them visualise the final design and enhance their comprehension of the complex issues involved.

Overview of the design

Songdo IBD's canal system is a key feature of the KPF masterplan. Mostly lying within the Park itself, where an extensive lake forms part of it, the canal system separates and connects the various areas of the Park and creates a key transport artery. It also provides waterfront development space to parts of the city, increasing real estate values as well as introducing cooling and biodiversity.

These multiple functions meant that the canal design involved several, and sometimes conflicting, drivers. These included:

- *Aesthetics:* The canals have to complement the areas through which they pass – sometimes organic and sinuous; in places hard and urban; sometimes within reach of passers-by; at other times remote. The most important aesthetic driver was for the canals to fit seamlessly with the environment but also be a key feature.
- *Water quality and conservation:* At all times the canal waters have to be of appropriate quality – not necessarily a perfectly clear crystal blue but nonetheless meeting criteria suitable for use. From the outset the canals were intended to enhance the ecology and biodiversity of the city. Also, while South Korea has wet summers, it can have very cold and dry winters, and so it was important that the waters be from a sustainable water source rather than pressure be added to the local water supply system.



7.

Some canal statistics

Volume of water:	110 000m^3
Flow rate:	30-285 litres/sec
Turnover rates:	Recirculation mode, 10-day flushing, five-day flushing
Length:	~1.8km
Maximum width:	110m
Minimum width:	17m
Length of rising main:	4.5km

8. The water taxi service.

- *Transport:* It was important that the canals be part of Songdo IBD's multi-modal transport system, and so this had a significant effect on geometry and layout and governed issues such as water depth, width, and headroom beneath bridges. The design also needed to accommodate space for maintenance, manoeuvring of boats, and water-taxi stops; here, Arup's transport planning and maritime teams advised the design team so that the canals could meet this functional requirement whilst retaining the overall architectural concept. A set of design criteria for dimensions, clearances, and impact loads became key influences on the canal design, and were developed locally to provide the water taxi service that opened in August 2009 (Fig 8).
- *Physical constraints:* Numerous constraints impacted the canal design, including clearance to bridge structures, long-term settlement of the ground surface, and high groundwater levels.
- *Sustainability:* The canal design was under way before the city instigated a systematic sustainability programme. However, the design premise embraced sustainability thinking from the outset through providing flexibility in flow rates for changing environmental conditions, the use of seawater as the water source, and avoidance of chemicals to treat the water – thus promoting a wide biodiversity in the longer term.

The canal system

Arup developed the design over a 30-month period, but the main elements of the system were established during three months of concept design in mid-2005. Despite rigorous testing, value engineering, and some challenges, these main design elements remained essentially the same throughout the project.

The water

There were several potential sources for the canal water, ranging from rain to groundwater to potable. The team made SWOT (strength, weakness, opportunity, and threat) analyses of each potential source and eventually decided on seawater. Whilst there was a plentiful local source for this, it was known from previous work on smaller-scale canals in Granton Harbour, Edinburgh, and Sentosa Cove, Singapore, that using seawater would involve numerous challenges, including water quality, ecology, tidal variations, sediment content, and salinity.

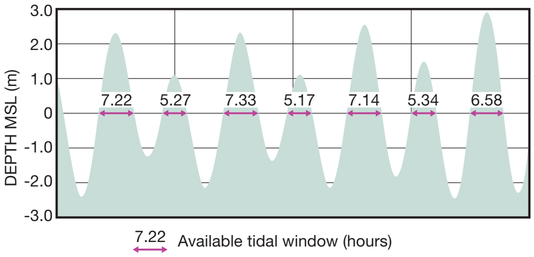
At an early stage, Arup advised on a sampling and testing regime for the seawater adjacent to the site, including physical, biological, chemical, and suspended solids parameters. Later, local university experts were engaged to identify the key ecological issues likely to occur and produce a canal ecology action plan. The main finding was the relatively high levels of nutrients in the seawater, which potentially can cause "red tides" – discolourations due to plankton blooms. Red tides harm fish and, when they die off, can release excessive organic matter causing anoxia (a decrease in the level of dissolved oxygen), inferior water quality, and odours. The canal design was aimed at reducing the risk of red tides occurring and providing measures to mitigate their effects if they do.

One initial rule of thumb was to achieve a 10-day flushing period; ie every 10 days "fresh" seawater equivalent to the entire canal volume would be introduced into the system so as to flush it and thereby reduce the chances of undesirable ecological conditions such as stagnation and algal blooms developing. As the design evolved, the ability to vary flow rate was introduced, allowing canal operation to suit changing seasonal conditions and water quality.

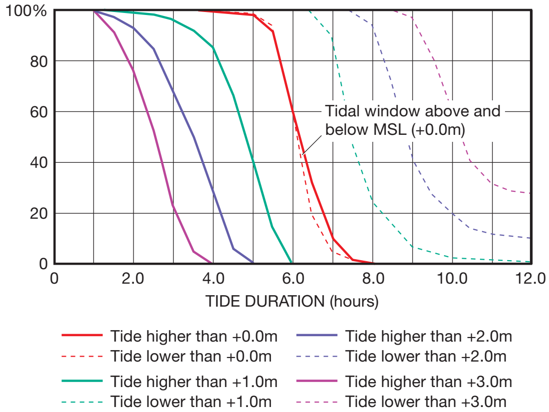
9. Sea wall at intake location prior to construction.

10. Sea wall intake after construction.

11. "Typical" variations in tidal window.



12. Duration of tidal windows for varying elevations.



Using seawater required substantial structures to take the water from the sea and then remove excessive sediments before introducing it to the canals. The intake and treatment works are on the corner of the reclamation footprint, some 4.5km from Central Park. Though distant, this location suited the future extension of the canal system to this area of the city and was also close to the sea where quality testing had shown generally less sediment in the seawater.

Seawater intake

The mud flats near Songdo IBD have a shallow gradient which, together with the high tidal range, meant that an offshore pipeline around 40m long would be needed to ensure that water could be extracted from the sea continuously. To avoid the cost and practical implications of this, the team decided that seawater would only be extracted at higher tide levels, so that the intake could be formed within the sea wall itself (Figs 9-10). The intake was designed so that the seawater would fall by gravity to a receiving chamber before being pumped to the treatment works or the storage pond. This meant that water would normally be pumped approximately 50% of the time.

Treatment works

The results of the seawater testing confirmed relatively high amounts of suspended solids. These varied by location, season, and state of the tide, but typically averaged 30-40mg/litre, peaking at 120mg/litre. If all this sediment was allowed to enter the canal, analysis showed that more frequent dredging would be required, the appearance of the water would deteriorate more rapidly, and anaerobic conditions would be more likely to develop. To reduce these risks, the team investigated the potential to remove sediment from the seawater.

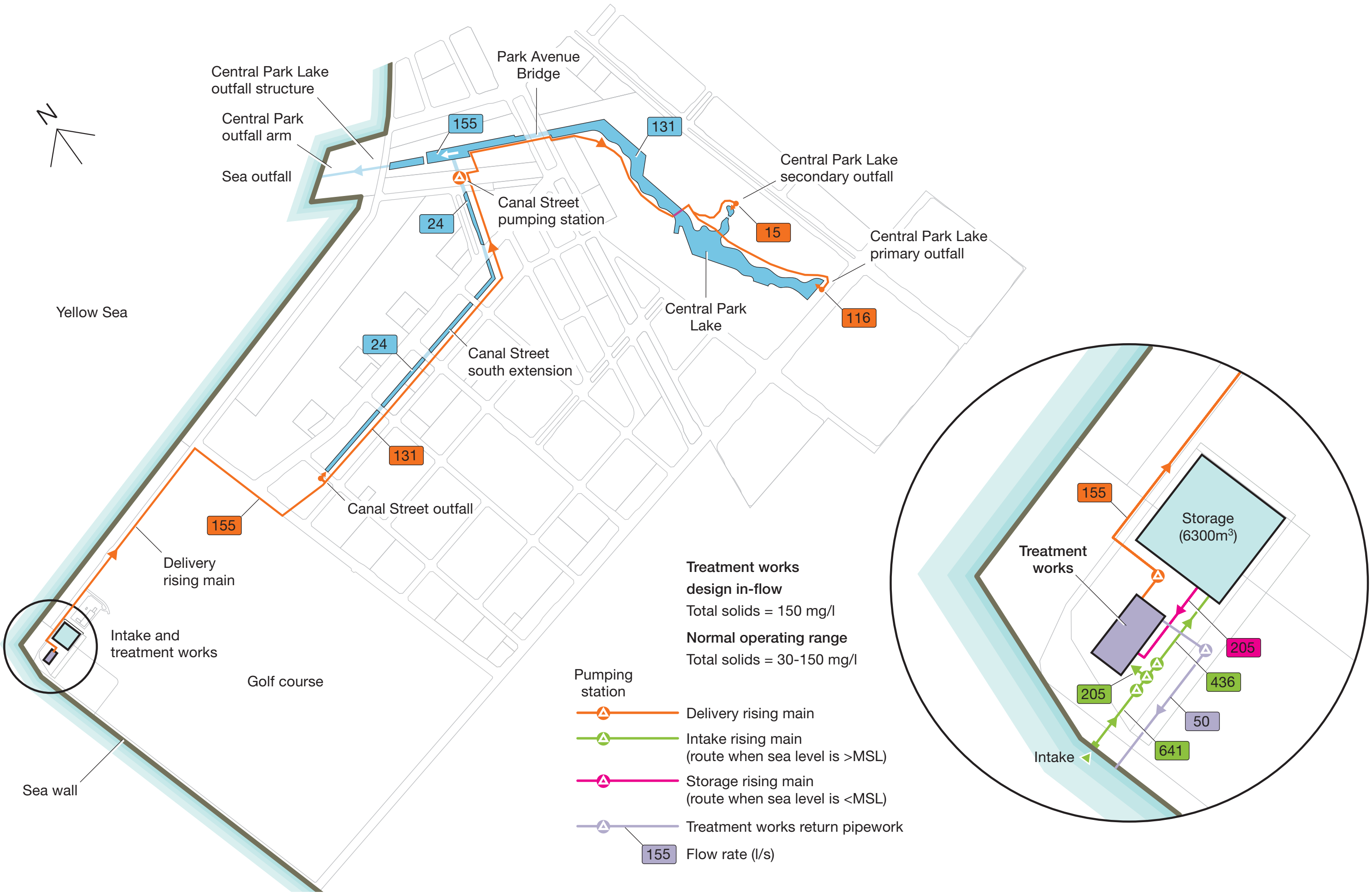
Many treatment options involve the use of chemical coagulants that could impact the canal ecology, so non-chemical filtration was identified as preferable. In brief, the treatment works comprise (1) screening to remove gross solids such as marine plants and animals and wind-blown debris, (2) self-cleaning depth filters, (3) media filtration, and (4) backwash treatment. All of these are housed in a locally-designed treatment works building.

Following value engineering and consideration of the issues involved, it was agreed that this process would be designed to remove 67% (by mass) or more of the sediment from the seawater, taking care of the larger particles that would be more likely to settle out of the canal water. The process would be modular so that the works could be expanded if additional treatment was required – if, for example, the sediment content in the seawater increased over time.

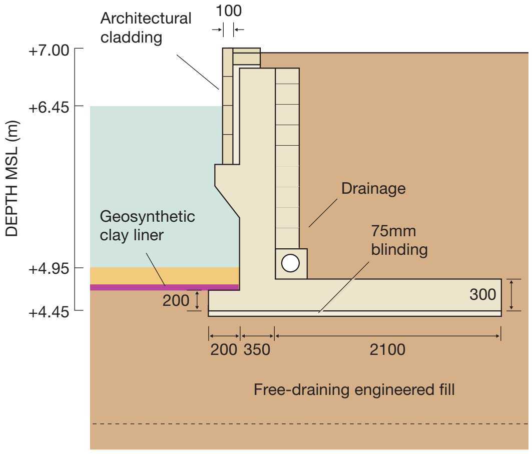
The need to remove nutrients as well as reduce sediment content was investigated, but was not deemed practical or cost-effective. Removing the solids should reduce some of the nutrient content and hence the risk of red tides developing in the canal system. This has since been confirmed during commissioning tests, which have shown that the levels of chlorophyll in the seawater are reduced as it passes through the treatment works.

Storage pond

Analysis of tide data determined how much seawater would need to be collected and stored to feed the canal while the sea is below the inlet level, and hence over what durations (Figs 11-12). An on-land water storage pond has been designed to accommodate 6300m^3 of raw seawater. This acts as a balancing pond, allowing a continuous supply during periods of varying availability of the source water, and enabling the treatment works to operate constantly over 24 hours rather than only at high tide periods. This has resulted in a more efficient treatment plant in terms of footprint, capital costs, and operational efficiencies.



13. 10-day operation – 10-day turnover, final condition.



14. One of the 12 various canal edge cross-sections.

Delivery pumps and rising (force) main

Treated water is pumped from the treatment works area to the canal via a 4.5km long, 500mm diameter rising main, the pumps being designed to operate in several modes, as follows, to give the canal operators flexibility:

- *Normal operation:* 10-day flushing rate (155 litres/sec). Water is pumped from the delivery works through the canal and back out to sea.
- *Boosted mode:* raw seawater pumped from the sea or storage pond and added to the treated water at up to twice the normal rate. This is for when ecological conditions in the canal mean there is a benefit to increasing the flushing rate, ie if algal quantities increase dramatically or high rainfall causes the canal salinity to drop.
- *Recirculation mode:* Rather than the canal water be allowed to discharge to the sea, it is recirculated by another pump and rising main, with new seawater only being added to supplement losses from the system such as evaporation. This mode is used when conditions at sea are undesirable, for example pollution/ contamination or high levels of algae.

Variants on these modes can also be operated, to allow for optimum operating procedures. For example, in winter when the risks of algal bloom formation are lower, the average flow rate in the canals can be reduced.

The pumps have been designed to deliver water to the canal system through outfalls at two locations at its eastern end (Fig 13). The system has a centralised supervisor control and data acquisition (SCADA) system, housed in the treatment works building. It provides real time data on canal performance, and allows operators to optimise the system and respond rapidly to changing conditions.

Canal structure

The canal's scale made it important to achieve an efficient, water-tight, easy-to-build structure that could be adapted to the various architectural edge conditions.
This involved techniques that were not normal practice in South Korea, but following exploration of numerous alternatives, were deemed most appropriate for the project. The basic cross-section is shown in Fig 14. The walls were constructed from water-retaining concrete whose crack widths are controlled in accordance with *BS8007*[1], thus reducing the permeability of the structure.

The risk of liquefaction within the reclamation fill below the canal walls was investigated to confirm that the proposed shallow foundation solution was appropriate. From detailed analysis of the grading of the reclamation fill, results of seismic cone penetration tests, and in situ soil tests, it was determined that the risk of liquefaction was low. If it did occur it would be limited to discrete horizons of weaker, less silty zones, and would not result in significant settlement of the canal walls.
To address the potential for zones of variable reclamation fill material below the base of the walls, a 1m thickness of fill below the wall footings was excavated and replaced with compacted, free-draining engineered fill to limit the potential for differential settlement between adjacent wall panels.

The base of the canal was formed by a geosynthetic clay liner (GCL). This had several advantages over other methods considered, including:

- straightforward installation with no welded joints, reducing the amount of quality control required
- simple interface with water-retaining concrete structures and penetrations such as bridge piers, requiring no mechanical fixings
- low leakage rates
- long design life
- accommodation of anticipated ground movements
- ability to "self-heal" if punctured
- compatibility with the saline environment.

Several GCL products are available. Most arrive to site in a dry form and are hydrated when the lined enclosure is filled with water. However, the GCL does not become readily hydrated if saline rather than fresh water is used, so here a pre-hydrated GCL was specified. Arup worked closely with the supplier to develop appropriate details for the canal construction. The GCL is itself covered with a protective layer that is in turn covered by gravel placed within a cellular geotextile mattress to protect the GCL from damage by water taxis (Figs 15a-e).

15. Canal bed construction: *Above* (a) Prehydrated GCL laid down on existing reclamation fill; (b) Soil layer added for soft protection of liner; (c) Recycled plastic honeycell layer filled with crushed stone to provide adequate protection cover; (d) Phased operations along canal; *Below* (e) Finished product.

Water levels and outfall structures

The canal water level was dictated by the level as it passes under Park Avenue Bridge (designed and built by a local firm through IFEZA), which spans between the Promenade and Sculpture Garden. Allowing for 2.5m water taxi clearance under normal operating conditions, this resulted in a water level of EL+6.45m, controlled by a series of weirs at the downstream (sea) end of the canal where it enters a 230m long, 1.2m diameter culvert before being discharged.

Hydraulic design

The treated seawater is pumped from the treatment works via rising (force) mains and flows into the canal at two locations; the primary outfall at the head of the Central Park lake and the secondary outfall at a more isolated part of the lake. During normal operation, the flows at each of these are proportioned according to the plan areas of canal that they serve.

A hydraulic model of the canal system was constructed using the Danish Hydraulics Institute *MIKE 11* software. This was used to simulate several scenarios relating to different operational conditions and potential storm events), and was particularly useful for checking headroom under Park Avenue Bridge, understanding how quickly levels could change in a storm, and optimising weir sizes. The model also showed that to empty the canal completely would take more than seven days.

Parking garage

Though it has 2700 car park spaces on three levels, the garage is entirely below the landscaped surface in the south-east corner of the Park. Its roof is designed to support small trees and shrubs, together with a *Madang* – Korean nomenclature for an open outdoor recreation and entertainment space (Figs 17, 20).


17. Aerial view of underground parking garage.

The car park footprint covers approximately 235m x 115m and is constructed 1½ levels below and 1½ levels above street level. It is intended both for Park users and the adjacent retail and commercial developments. A planned pedestrian bridge and a below-ground vehicle ramp will connect the garage to the Convention Center and the 65-storey North East Asia Trade Tower (NEATT) complex across the six-lane street that borders the eastern end of the Park. Vehicular access to the garage is from two separate entrances at street level connecting to the lower and mid levels, while pedestrians can get to all levels via several kiosks or bulkheads dotted around the landscaped areas on the car park roof.

The landscaped surface above the garage required fill to a maximum height of 6.7m above roof level. To limit loading on the roof slab and minimise the size of the structural elements and foundations, a maximum soil depth of 1.2m was agreed – the minimum needed to sustain grass, shrubs, and small trees – and the remaining height provided by lightweight expanded polystyrene blocks.

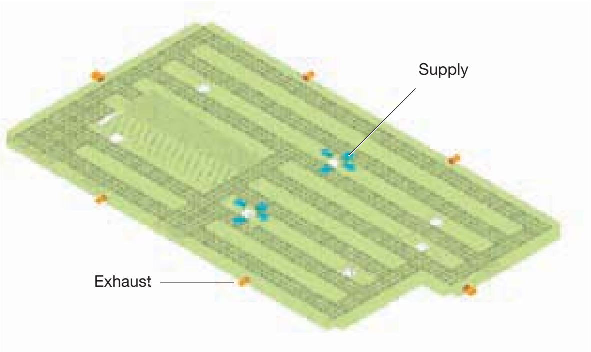
A reinforced concrete two-way flat slab framing was selected as the most efficient structural solution, and to minimise excavation depths. The column spacing is 8m x 8m, and the typical parking floor structure a 275mm deep flat slab. For the more heavily loaded roof slab, a 375mm deep two-way slab with 2.75m x 2.75m drop panels, 375mm thick, is at each column location. Lateral stability derives from the perimeter retaining walls as well as the reinforced concrete walls around stair cores.

The 600mm square reinforced concrete columns do not form part of the lateral resisting system. The basement walls, which all support soil to varying depths around the garage perimeter, have been designed for the soil and hydrostatic lateral loads, as well as for lateral stability due to wind and seismic forces.

16. The Mountain Strolling Garden Bridge (see p14) leads to the parking garage.

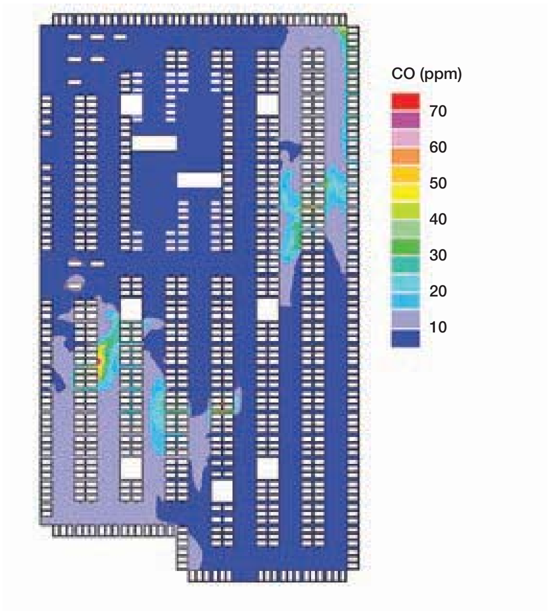
As with many of the Songdo IBD structures, 450mm diameter precast, prestressed, hollow concrete (PHC) driven piles were adopted for the foundations. The base slab, typically 450mm thick, spans between pile cap locations due to the poor quality of the soils immediately beneath, and is designed to resist both gravity loads from the lower parking level and uplift water pressures from the long-term groundwater levels that may rise to within 1m of the adjacent street levels. The perimeter piles were designed to accommodate negative skin friction (downdrag) loads due to settlement of the soils from landscape filling immediately adjacent to the garage walls.

The garage is not heated or cooled except for enclosed lobby areas connected to conditioned spaces such as the pedestrian footbridge to Block 36. All levels, and the ramp areas for entering and exiting, are mechanically exhausted to prevent build-up of carbon monoxide (CO) and other pollutants. There are exhaust points throughout the garage, and outside air is introduced to all parking areas by areaways and fans. Throughout, induction fans move air between intakes and exhaust points.



18. CFD model input showing location or perimeter exhaust and central intake positions.

19. Output of CFD analysis showing CO concentration contours at 1.1m above floor level.



20. Landscaping above the underground parking garage, showing bulkhead access.

Due to the garage's large plan area, a CFD (computational fluid dynamics) study was carried out to validate the design of the mechanical ventilation systems – six exhaust locations around the perimeter plus two intakes at the central cores – and demonstrate that gas concentrations throughout the parking area were acceptable (Fig 18). The prediction of maximum CO concentrations did not exceed 200pm under worst-case scenarios of lengthy idling times, with the maximum predicted value in the middle of the occupied zone (coinciding with children's height) never exceeding 120ppm (Fig19).

The electrical supply is directly from the Korea Electric Power Company (KEPCo) network, with an incoming service at 22.9kV. A unit substation within the parking structure steps the voltage down to 380Y/200V, three-phase, four-wire, to serve all building loads. A diesel-powered emergency generator is provided for emergency and life safety loads. Internal illumination is from 175W metal halide fixtures at 4m centres, with quartz restrike for emergency lighting/restart on every fourth fixture.

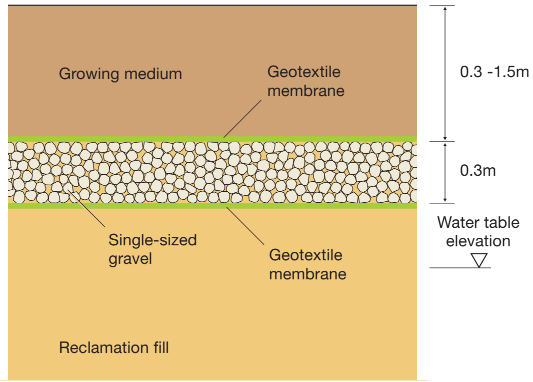
The garage's large footprint does not allow for full surface stormwater drainage from the park area (Fig 20) supported by the garage roof slab. Surface drainage in the Park diverts most of the rainwater away from the garage structure, but some runoff is allowed to drain into the parking structure below. This excess stormwater, mainly from the plaza above and specific areas within the garage, is collected and conveyed through branch piping connecting to stacks and horizontal storm house-drains. These flow by gravity through the perimeter wall, leading to exterior municipal storm sewers. All storm drainage from areaways below the gravity storm house-drains are piped to the lower level, where a drainage layer is constructed on top of the structural base slab due to the local requirement for no underslab piping systems. Water is then pumped from sumps around the parking floor area.

The parking garage is fire protected by a dry pipe sprinkler system. Each zone covers 3000m² and each sprinkler head protects an area of 2.3m radius.

The Park

Grading plans

The Songdo land reclamation area had little to no topographical variation, so Central Park has been sculpted to pay homage to Korea's topography. The rolling geography includes the countryside, mountainous coastlines, and various other landscapes. In creating this vision, soil was locally imported from various other sites in Songdo IBD being excavated for building foundations and below-grade parking. Apart from minimising waste, the grading helped fulfil other project goals – minimising soil erosion, maximising collection into the rainwater harvesting storage units, and helping to create a better environment for plant species to strive in a harsh marine environment.



21. Remediation strategy for growing medium.

Remediation strategy

To protect the landscaping from saline groundwater in the reclamation fill, a capillary break layer is provided to separate the growing medium from the underlying reclamation fill (Fig 21). The thickness of the growing medium typically varies from 0.3m (for grass areas) to 1.5m (for large trees planting). The capillary break is formed by a 300mm layer of single-sized gravel that is bounded by geotextile layers at the top and the bottom to ensure the gravel does not become clogged. The underside of the capillary break layer will always be higher than the maximum high groundwater level, which is defined as +5.5mEL (ie 5.5m above mean sea level). To minimise costs and resources, the capillary break was designed to incorporate drainage pipes as part of the overall Park surface drainage plan.

Rainwater harvesting

As Korea has very extreme weather patterns, Central Park was designed to maintain a balance between rainwater storage and its irrigation needs. Various irrigation sources were explored – greywater, rainwater harvesting, groundwater, seawater reverse osmosis, and the local municipal water supply. The design team reduced irrigation demand as much as practicable through a planting scheme that favours species with low water demand, and NSIC agreed to install underground storage elements for approximately 5400m^3 of rainwater falling within the site boundary. This is stored through the dry winter months when there is no irrigation demand, and provides water for irrigation in the spring when temperatures rise. Water demand peaks during May, prior to the wetter summer months. Before the stored water can be used, it is filtered through an ultraviolet system. This helps ensure that any bacteria that may have formed during storage are cleaned out prior to use.

Park architecture

The smaller buildings are designed to a common theme and architectural finish, with wood trellis/glass cladding envelope and marine grade timber decking where they border the canal. The exceptions are the three Korean Pavilions, the design of which was carried out by the local design teams. Each is supported on piled concrete plinths installed when the other Park structures were built.

22. Park Path Bridge at night, showing feature lighting (see pp14-15).

23. Strolling through Conifer Garden.

24. Exterior of Boathouse West.

25. Children's Play Zone (Blocks D22 & 23 in background)

The buildings in the Park include:

- *Boathouse East:* located at the head or top end (north-east) of the Park opposite the NEATT, and the main access for the water taxi service; single-storey steel-framed structure accommodating ticketing, waiting areas, cafeteria, and restrooms
- *Boathouse West:* water taxi stop located within the Promenade area or bottom end (south-west) of the Park; single-storey steel-framed structure with waiting areas and restrooms (Fig 24)
- *Visitors' Centre:* two-storey steel-framed structure housing information services and restrooms.

All the buildings are supported on 450mm diameter PHC driven piles.

In addition, various smaller architectural features are accommodated within the Park boundary.

The Therapeutic Zone is a walkway where citizens take off their shoes and walk barefoot on various surfaces intended to hit pressure points in the foot to create a therapeutic experience. This pathway also includes an elevated body of recirculated water cascading along its side.

The Children's Play Zone provides a safe play area with a shallow watercourse running under two curvilinear concrete bridges, both clad with granite blocks (Fig 25).

Finally, at the north-east corner, visitors enter the Park via an informal entrance where the main path leads through the Stone Passage into the Mountain Strolling Garden. This passageway has huge shards of granite rising up to 4.8m above path level, creating a sense of "rite of passage" (back cover illustration).

26. Park Path Bridge in context, with part of the ecology centre at the bottom left.

Footbridges

Two footbridges, both designed by Arup, cross the canal – Mountain Strolling Garden Bridge and Park Path Bridge. The architectural form was selected to match the "flow" of the Park and the masterplan vision, eg the curvature of the bridge architecture reflects the curved roof form of the Convention Center to the east. The tilted arch and deck profiles were kept low to maintain pedestrian visibility into the Park, while the arches extend from below to above the deck so as to draw pedestrians and cyclists into a changing experience across the bridge.

Both bridges have a similar basic design, with tilted main load-carrying arches complemented by a more gradual deck arch. The main arches are tied to the deck arches by vertical tube members, creating a vierendeel style truss arrangement. The deck arches also tie the main arches, helping to reduce the amount of arch thrust taken by the foundations. The decks are sustainably harvested Ipe hardwood planks, complementing the steel superstructure's silvery-white finish.

Mountain Strolling Garden Bridge is 52m long with a gently arching 4m wide footpath, connecting the plaza over the parking garage with the Mountain Strolling Garden (Figs 16, 29). It is configured as a 2½-span arch bridge. The 30m main span is carried by dual tubular steel arches rising above the deck and tilting inwards. The height of the arch and the inward tilt were designed to create an ideal spot for leaning and enjoying the view. The two side-spans are 16m and 6m respectively and again comprise dual tubular steel arches, here each arch just reaching deck level.

27. The deck surface of Park Path Bridge, with blocks D22 & 23 in the background.

Park Path Bridge is a wider, two-level single-span arch 50m long, spanning both the canal itself and the walkways on each shore. The superstructure is four tilted tubular steel arches (the outer two lean out, the inner two lean in), all rising above deck level. The four arches force the deck to split into three separate spaces at mid-span; the outer two sections are 2.5m wide and follow the gentle curve of the deck arch, while the middle space rises with the two central arches creating a raised walkway of variable width in the middle of the bridge, forming space for leisure and more importantly, interaction (Fig 27). Separating pedestrian flow across the bridge creates a variety of spaces – all part of a deliberate effort to create a bridge that is as much a destination as a passage across the canal.

Lighting

Lighting is integral to the Park design. Close collaboration between Arup, KPF, and the local lighting teams was needed to follow the vision through to reality on site. The key elements are:

Garage feature lighting: To create a connection to the outside, and exploit an opportunity for architectural feature lighting, the walk-on glass skylights in the plaza area above the roof of the parking garage are dramatically lit. Long-life, high colour rendering sources create a key night lighting effect in the Park's higher elevation where the glass skylight resembles a "lit carpet" at this position overlooking the canal. Perpendicular to the "lit carpet" skylights are feature textured glass walls to connect the parking structure to the canals. Here, long-life, asymmetrical LEDs frame the feature glass at night and give an ambient glow to these respite areas of the Park, overlooking the canal.

Boathouse architectural lighting: To support the transitional architectural nature of the boathouse structures, the lighting here allows transparency through the floor to the ceiling glass at night. This balance of quality light from the interior to the exterior accentuates the connection between them. Key interior elements are lit appropriately, at the same time giving the structures a night-time lit iconography. The light sources are long-life and energy-efficient as befits the project's sustainable agenda, as well as extending maintenance cycles.

Bridge lighting: The bridge steelwork is highlighted at night by "sculpting" light around the key elements to form a soft glow for pedestrian movement. Small ceramic metal halide luminaires create a unique white light composition against the vertical structural elements, working to reinforce the scale and purity of the bridge structure. To assist pedestrian movement, custom handrails have integrated warm colour temperature, long-life LEDs. This additional gentle layer of light distinguishes the movement zone from the sculptural elements of the bridge.

28. Night-time along the lake (NEATT and Convention Center in background).

29. Path leading to Mountain Strolling Garden Bridge.

Commissioning, filling and operating the canal

From the outset, it was clear that the seawater canal presented a fantastic opportunity to bring interesting, varied, and sustainable marine ecology into the Park. However, several potential issues would have to be overcome, particularly in the first few years of operation while the biodiversity within and adjacent to the canal became established. During the canal design, Arup provided guidance on the operation and maintenance to come, included advice on ecology, treatment works, day-to-day maintenance, and assistance during the filling phase.

Canal ecology

At scheme design stage, Arup advised NSIC about commissioning three studies by local professors: on the prediction and management of potential red tides (Professor Hae Jin Jeong, Seoul National University), on the canal ecology (Professor Eun Ju Lee, Seoul National University), and on biodiversity (Professor Yang Seop Bae, University of Incheon).

Arup used their findings and recommendations to produce a canal ecology action plan that covered, amongst other things:

- monitoring, prediction, and control of potential red tides
- the potential for formal planting within the canal
- establishment and control of biodiversity
- potential sources and mitigation of pollution
- general planned maintenance.

The team recognised that it would take several years for the canal ecology to become established, so the operation and maintenance (O&M) regime would need to be constantly developed over time. Arup recommended engaging specialist local consultants with a good knowledge and understanding of water quality and local ecology, and wrote a scope of works for this role and assisted with the appointment of a team from Hanyang University led by Professor Moonil Kim. Since then, Arup has worked closely with the University, the contractor, and the NSIC team to finalise plans for filling, commissioning, and operating the canal, and has provided a site presence during this period. The main developments of the design and operational strategy produced as part of this study were:

- proposal of a regime for monitoring water quality and predicting red tides and other adverse ecological conditions. Several potential measures for dealing with these were suggested, ranging from temporary alterations to the canal flows and introduction of physical mitigation measures, to biological or chemical control. Some of these are being trialled during the first year of operation.
- an in-depth study of the potential advantages and disadvantages of formal planting in the canal. This concluded that, for the time being, no planting would be actively introduced, but rather that the canal operators would need to actively manage any plant-life that does develop – in particular, ensuring that it does not become too intrusive in water-taxi corridors or cause anoxia following a die-off.
- drafting of a canal ecology O&M manual. This advises the canal operators on likely ecological conditions in the canal, how they should be established and managed and, in the event of problems being predicted, avoidance or mitigation measures. This included advice on filling of the canal.

Arup continues to work with Hangyang University and the local design and construction team to develop the O&M regime as the canal becomes established. In the longer term, Arup will get valuable feedback on canal performance for improving the design of future canals and other large seawater features such as lagoons and marine lakes.

Treatment works

Another main element of the commissioning and operation phase for which Arup provided specification and advice was a pilot treatment plant. This was developed to test and refine the treatment method and was installed some six months before construction of the treatment works proper. It also provided the first data on the water quality following removal of sediments, and thus gave an important early input into the canal ecology studies. Arup also provided specifications and scopes covering performance of the final works, commissioning and testing, and requirements for the O&M manual.

Final commissioning of the treatment works could not be carried out until the canal was full and had been operational for several days.

30. Plants and trees with low water demand were favoured.

31. Stone canal edge. The 65-storey NEATT, almost complete, is in the centre background.

As explained below, the programme for this was critical and, when some inevitable challenges were encountered, Arup supplemented its local site-based staff with the lead MEICA designer for the scheme at very short notice to ensure that commissioning went as smoothly as was practical.

Filling of the canal

Construction of the canal structure and MEICA works were programmed for completion towards the end of June 2009, and the aim was to have the canal filled and operational in time for the official opening of the Park on 7 August, for the start of the three-month Incheon International Festival. Arup worked with the NSIC PD team, contractors, university, and design group to develop a filling and testing plan to ensure that the canal could be "open for business" by this date. This allowed for filling gradually as the systems were tested and canal ecology was monitored, with a gradual increase in the rate of filling over time.

Filling was completed several days prior to the official opening to ensure the appropriate length of time needed to refine the operational procedures with a short contingency period.

Unfortunately, some two weeks prior to filling, at the end of the monsoon season, Songdo IBD had a huge six-hour overnight storm. As the Park vegetation was not yet established and so did not prevent as much run-off and soil reaching the canal as will be the case in the future, approximately 300mm of stormwater with some sediment washed into the canal, which also suffered some minor damage along the bottom.

Arup and the University quickly identified that these conditions, together with the likelihood of further rain, the high sea and air temperatures, and the relatively slow rate of filling, were just what could initiate red tide or algal bloom conditions. Bearing in mind the desire to have the canal full on opening day, but also the consequences of having a poor canal ecology develop during the Festival's early stages, careful consideration was given to whether filling should be delayed to allow the canal to be cleaned and emptied. Arup decided, together with the client team, to start filling on schedule but to monitor the water quality very carefully and collectively respond to any issues as they became apparent. This required Arup's site representative to liaise daily with the local teams and the firm's specialists in the US and UK so that information, data, and ideas could be circulated and important decisions made as required.

The canal was filled successfully on time on 3 August for the Park Grand Opening just a few days later. The water quality continues to be monitored by the University. As expected, it constantly varies but there have not yet been any requirements for active mitigation to maintain water quality. The University will have a major role to play in monitoring and advising on water quality for months or even years as the system and ecology become established and understood.

32. Fans enjoy boating in the canal at the grand opening of Incheon International Festival.

Coastal flood risk – added value for LEED-ND accreditation

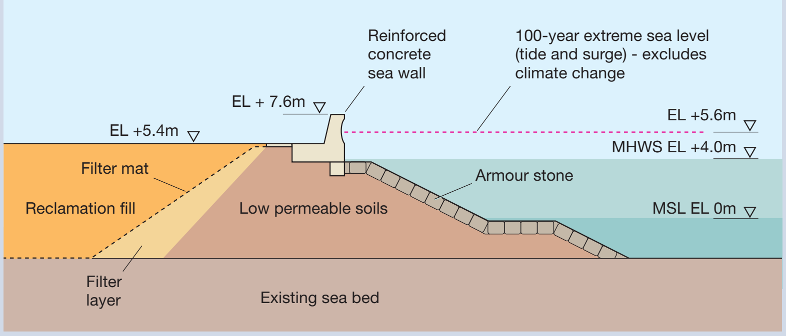
Beyond Central Park, Arup's role in the canal design directly impacted on a wider Songdo IDB flood assessment to provide timely and robust input to the city's sustainable accreditation.

As part of the initial reclamation works in the early 2000s, the local government and its engineers built sea walls around what would be the western and southern sides of the city (the eastern area is still being reclaimed). As developer, Gale International needed to know the level of flood risk as it was piloting the project with the LEED-ND (Neighbourhood Development) accreditation scheme*. One LEED-ND requirement is to satisfy the floodplain avoidance SLLp6 category, termed a "prerequisite". This, however, is written around US-based procedures and refers to flood insurance maps produced by the Federal Emergency Management Agency (FEMA) available within the US only. Arup helped propose alternative Songdo IBD criteria for submission to the LEED-ND panel.

The scheme requires compliance with set criteria in relation to flooding, and the coastal, non-US location made this difficult. Previous work by Arup on the seawater intake enabled the team to provide guidance, and so Gale International commissioned a coastal flood risk assessment. Arup drew on the previous tide window statistical assessment made during the canal design phase, but now focused on assessing whether the site was at risk from a 1-in-100-year flood event (a 1% likelihood of occurrence in any year). Since there are currently no available predictions of 1-in-100-year extreme sea levels around the South Korean coast, Arup used data it had already gathered for the early design phases from NORI (National Oceanographic Research Institute), a South Korean government organisation.

Using this extensive data set of hourly, daily and monthly sea level measurements taken from 1960 to 2009 at Incheon and Wolmido Tidal Stations, 7km from the site, Arup carried out a statistical analysis and created trend lines to predict the extreme sea levels for a range of return periods and compared them with reclamation and sea wall levels (Fig 33) which concluded that the sea wall would defend the site from a 1-in-100-year extreme sea level event. The knowledge gained here can aid similar assessments for other LEED-ND projects worldwide.

33. Cross-section of sea wall (south revetment).



Grand opening and conclusion

The canal was filled successfully on time on 3 August in perfect time for the grand opening ceremony of the Park on Friday 7 August, 2009. The Mayor of Incheon, together with representatives from IFEZA, Gale International, POSCO E&C, and other notables, attended the festivities and were able to enjoy the first water taxi-ride along the canal. This made one full loop, starting at the east end of the Park at Boathouse East near the NEATT to the opposite west end at Boathouse West, passing along the way the Ecotarium, several government buildings, the future museum site (all locally designed), under the Park Avenue Bridge, and finally back to its origin.

Central Park and the canal were very well received, and throughout the opening day caused great excitement, which has continued to the present. Citizens enjoy the canal, use water taxis and paddle boats (seasonal) for the children, walk along the endless paths, and take in all of the landscaped features that this modern-day creation has to offer.

With Central Park now complete and open, other facilities in Songdo IBD are set to be launched one by one. Bordering the Park, Songdo Convention Center opened last October, and the NEATT is under construction along with the new commercial complex and several new government offices to form the heart of the city.

Arup is heavily involved in several other projects in Songdo IBD beside the NEATT and the Convention Center. Mixed-use areas at Block 125 and Blocks D20-22, as well as the Jack Nicklaus Golf Club Korea, are currently under construction. Ongoing in the design phase are the mixed-use Blocks D24, F3 and F5, which once built will complete the loop around Central Park.

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* LEED-ND is a pilot system produced by USGBC (US Green Buildings Council) for rating and certifying green neighbourhoods. It is becoming one of the leading industry standard accreditation systems sought for civil engineering projects and is already being employed outside the US.

33. Central Park and its canal within the context of Songdo IBD.

Ashok Raiji is a Principal of Arup in the New York office. He is the Project Director for the project and the main client contact with Gale International.

Robert Talby is an Associate of Arup in New York. He is currently the Project Manager and leads all geotechnical works for Songdo IBD.

Rachel Nicholls is a Senior Associate of Arup in the Melbourne, Australia, office. She was the former Project Manager and lead for all geotechnical works in Songdo IBD.

Sherazad Mehta is a senior engineer with Arup in New York. He acts as Deputy Project Manager for the project and is lead designer for the civil design for the Park.

Steven Lesser is an Associate Director of Arup in the Manchester, UK, office. He acts as Project Manager for the canal design carried out in several UK offices.

Tom Saville is a senior engineer with Arup in Manchester. He acted as Deputy Project Manager for the canal design.

Special thanks to **Kevin Wegner** and **Joon-Hyuk Lee** from KPF for providing many of the images.

Credits

Client: New Songdo International City Development LLC (Gale International *and* POSCO E&C) **Architect/masterplanner:** Kohn Pedersen Fox Associates PC (KPF) **Multidisciplinary engineer:** Arup – Eddie Carmichael, Vicky Carr, Ian Carradice, Richard Chamley, Cossel Chang, Jonathan Crince, Andrew Cushing, John Davies, Mike Evans, Matthew Franks, SY Ha, Andrew Jackson, Ivan Jelic, Yong-Wook Jo, Tom Kennedy, Isabelle Lavedrine, Vincent Lee, Seungwon Lee, Clare Leech, Steven Lesser, Sherazad Mehta, Roger Milburn, Pablo Miranda, Isabelle Moriera, Rachel Nicholls, Michael Nichols, Mark Pearson, Richard Potter, Ashok Raiji, Mark Roche, Tom Saville, Eric Sekulski, Alex Schnayder, Marcus Schodorf, Malcolm Smith, Tom Smith, James Sowden, Brian Stacy, Robert Talby, Chris Taylor, Martha Taylor, James Theobalds, Rob Thorne, Mia Tsiamis, Clon Ulrick **Cost consultant:** Davis Langdon & Seah Korea **Local architect/engineer:** Yooshin Engineering Corporation **Horticulturalist:** Vonder Design Group **Illustrations:** 1-4, 7-8, 16, 20, 23-27, 29-32 34 KPF and HG Esch; 5 Gale International; 6, 11-14, 21, 33 Nigel Whale; 9 Mark Pearson; 10, 15, 22 Mike Evans; 17 Ashok Raiji; 18-19 Arup; 28 Joon-Hyuk Lee.

Reference

(1) BRITISH STANDARDS INSTITUTION. *BS8007:1987*. Design of concrete structures for retaining aqueous liquids. BSI, 1987.

1. Overview of the flat rolled product facility designed and project managed by Arup.

Asia Aluminum flat rolled product facility, Zhaoqing, Guangdong province, China

**Chi-Lung Cheng Bruce Chong Paul Clarke Ricky Lee
Daniel Ma Osward Tang Raymond Tsang**

2. Entrance to Asia Aluminum Industrial City.

Arup carried out the full multidisciplinary design and project management for this, the largest aluminium flat rolled product facility in China.

Project background

Asia Aluminum (China) Co Ltd is registered in China for the manufacture of aluminium products, as well as secondary forming and fabrication (extrusions). The company is based in the Zhujiang (Pearl River) Delta, which now plays an important role in the aluminium market. Coupled with shifts in domestic consumption, this has resulted in significant changes in the variety, size, and quality of products.

The new flat rolled product (FRP) facility is a factory for manufacturing aluminium strip, sheet, plate, and hot rolled coil to various specifications. Its products are largely for domestic Chinese use (a burgeoning market for aluminium canning and packaging products), but are also of appropriate export quality.

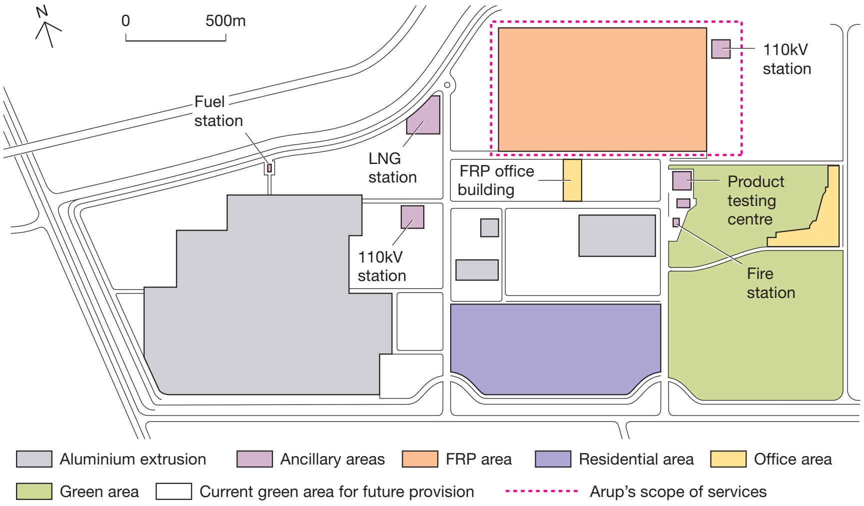
Domestic suppliers cannot currently meet market demand, and imports of strip and plate aluminium have grown. At the same time there has been an increased need for high-precision and high-quality aluminium strip and sheet products in overseas markets. These include can body stock, top grade lithography sheet, coating sheet for automotive and watercraft, aerospace materials, and other specialist requirements.

These market conditions have been the main drivers for creating Asia Aluminum Industrial City, an integrated aluminium production/fabrication facility that uses high technology to provide high-value products in a low-pollution environment.

Asia Aluminum's successful establishment has contributed to upgrading the domestic industry, increasing supply efficiency, and significantly reducing the current dependence on imported high-precision aluminium products.

Asia Aluminum has been developing Industrial City for several years, and its overall area is now in excess of 4.3km^2 (Fig 3). The entire development currently includes 985 000m^2 of factory floor area, 75 residential blocks and 21 executive villas housing up to around 4000 production personnel, a nine-hole golf course with a driving range, corporate headquarters, fire services station, laboratories, and all necessary supporting infrastructure.

The whole of Industrial City is surrounded by a boundary "moat". The 480 000m^2 Phase 1 FRP facility was completed in July 2009 with a production capacity of 400 000 tonnes per annum. Phase 2, currently on hold, is intended to more than double this output.



3. Asia Aluminum Industrial City masterplan.

Initially, Asia Aluminum employed a Local Design Institute (LDI) in China for the FRP facility, but the need for fast-track delivery, effective communications with major European and North American process equipment suppliers, and simultaneous design development with the process plant and equipment design, caused the company to engage Arup in 2005 for the full multidisciplinary design and project management (PM) of the flat rolled product facility (Fig 3).

Overview of structures

The main factory buildings are single-storey, multi-bay portal structures 10m-20m high, spanning either 24m or 30m, with portal frame spacing at 6m or 7.5m. The portal columns are precast reinforced concrete with roofs in structural steelwork, and the roofs and walls covered with corrugated steel sheeting (Fig 4). Precast prestressed concrete pile groups were generally adopted to support the building columns. Overhead travelling cranes supported on the factory building columns serve the production process. Depending on production requirements, their lifting capacity varies from 25 to 150 tonnes.

The process equipment foundation (PEF) structures are of in situ reinforced concrete, supported on 1-1.2m diameter concrete bored piles. All the PEF structures are below ground level, the lowest chamber being at -17m. Due to high levels of groundwater, waterproof concrete in accordance with the China Code of Practice[1] was used, with waterproofing applied to the external concrete face. The PEFs' concrete profile is complex and custom-made for the equipment to be supported. Construction had to be to highly precise, or the process equipment would not be set to the precise alignment required to maintain the production quality of the flat roll product.

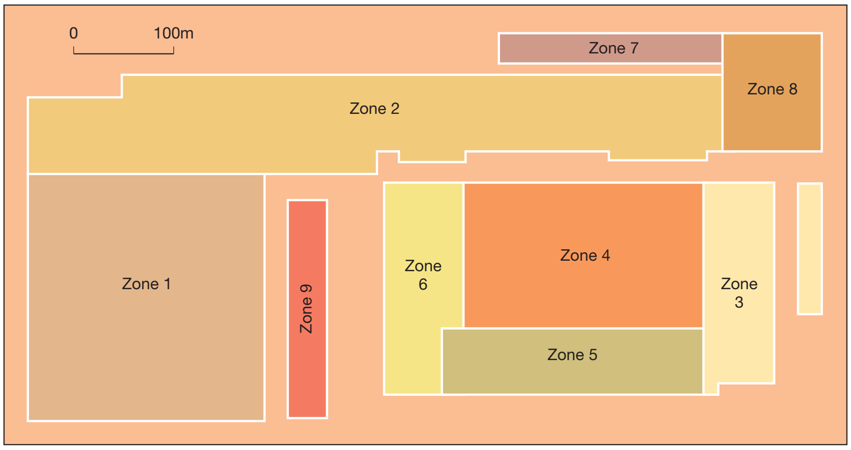
4. Typical factory building showing concrete columns supporting the structural steelwork.

Structural statistics

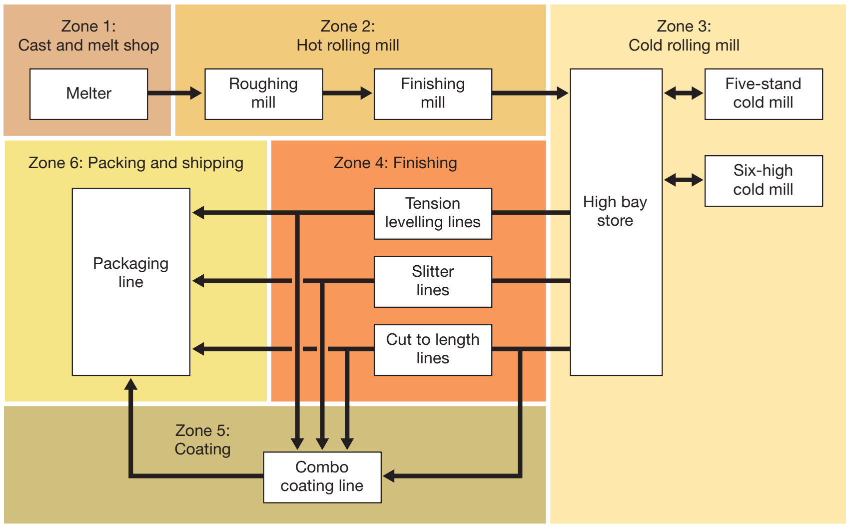
- factory floor loading: 3-10 tonne/m^2.
- volume of concrete: 24 000m^3
- quantity of structural steelwork: 15 000 tonnes
- area of roof and wall cladding: 213 000m^2
- total connected power capacity: 185MVA (Phase 1); 316MVA (including postponed Phase 2)
- total cooling water capacity: 190MW
- length of hot mill: 435m
- hot mill rolling speed: 4m/sec roughing mill; 8m/sec finishing mill
- weight of each finished strip coil: about 20 tonnes
- automated coil store: 42m height; storage capacity approximately 2000 coils.

The manufacturing process

The FRP facility's core function is to produce aluminium plate and sheet in coils, and different kinds of aluminium products from raw materials. It will probably be the largest facility of its kind in China when fully operational. Basically, imported raw materials are melted and initially cast into 20 tonne slabs, which are rolled into plate products in the hot mill and from plate products into sheet in the cold mill. Both plate and sheet are produced from the coils, which weigh around 20 tonnes and are stored in the high bay store. The sheets can be further processed into products such as can bodies and building products. For the whole manufacturing process, the facility is divided into nine zones (Figs 5, 6).



5. FRP layout.



6. Process flow in the FRP.

Zone 1: Cast and melt shop

Here the slabs are produced from the raw materials. Zone 1's floor (some 62 000m^2) houses six melting and holding furnaces (four 85 tonne; two 50 tonne), three ingot casters, an ingot saw, and an ingot scalper. The latter perform the basic shaping of raw ingots, with the scraps from the process collected and taken back to the melter. Space is reserved at the zone's southern end for Phase 2 expansion to house a further pair of melting and holding furnaces, and one ingot caster.

Zone 2: Hot rolling mill

In this 40 000m^2 building the slabs are reheated in a pusher furnace prior to entering the hot rolling process, first in the roughing mill and then in the finishing mill (Fig 7).

The roughing mill produces 80-150mm thick plate from slabs 400-590mm thick. The finishing mill further reduces the strip thickness to 2-8mm. The factory includes 8500m^2 for future provision, with space reserved near the pusher furnaces for a future (fourth) pusher furnace.

Zone 3: Cold rolling mill

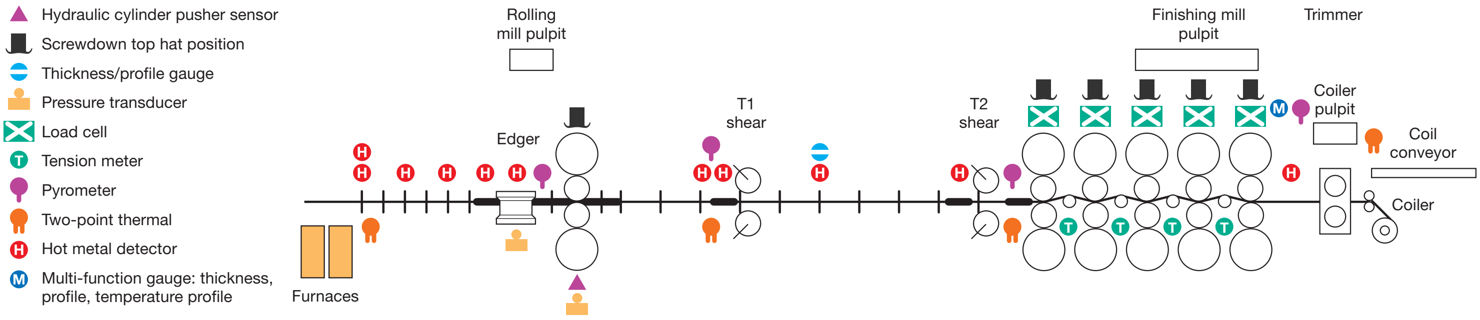
This area consists of three sub-zones: 3A, 3B, and the high bay store.

The 3200m^2 Zone 3A is the roll storage shop.

Zone 3B houses a five-stand (ie five sequential rollers stacked vertically) cold mill and a single-stand six-high cold mill in a factory floor area of 11 340 m^2. Aluminium coils produced in Zone 2 are fed to these two cold mills to produce coils of aluminium sheets 0.15-6mm thick.

The high bay store, 18m x 220m on plan and 45m high, comprises three rows of storage racks structurally connected to the building's external cladding. As well as operational loading, they are designed to resist lateral wind and seismic load. Here are stored the coils produced in the hot and cold mills, transported through an automatic coil transfer system. This facility is specially designed to receive coils after production in a hot state and allow them to cool to ambient temperature during storage.

7. Hot rolling mill layout.



8. Rolling table and overhead crane in Zone 2 hot rolling mill.

9. Shearing process equipment in Zone 2 hot rolling mill.

Zone 4: Finishing

Zones 4-6 are grouped together in one single-storey building. Zone 4 (approximately 36 000m^2) accommodates the equipment for treatment and forming to produce different kinds of aluminium products from strip, eg can bodies and building products (Table 1). Space has been reserved in this zone for more production lines including four anneal furnaces, heavy tension levelling line, and heavy and light slitting lines.

Tension levelling stretches and bends aluminium coil, cleaning and eliminating the internal stress both laterally and longitudinally, as well as removing the oil trace and aluminium powder that can accumulate on the strip surface during rolling. The slitting line cuts and divides the aluminium and its alloy coil into several strips of different widths, while the cut to length line cuts it into board and sheet with different widths and lengths. The strip cleaning line obtains good quality on the surface of aluminium coils after rolling on cold rolling mills.

Zone 5: Coating

The 19 000m^2 Zone 5, south of Zone 4 in the same building, houses the combo coating line, used for alloy coating and painting aluminium coil products. Space is reserved on the north side of Zone 5 for a future second coating line.

Zone 6: Packing and shipping

Zone 6, west of Zone 4, occupies about 16 000 m^2 for packing and preparing for shipment of finished aluminium products.

Zone 7: Plate department

This zone, in a single-storey 6900m^2 building, takes aluminium plate stock from the hot mill and shapes it to the required dimensions for further fabrication.

Zone 8: Roll shop

The four grinders in this 6900m^2 zone maintain the rollers used in the hot and cold mills.

Zone 9: Utilities

This large stand-alone utility area between Zones 1 and 6 is partitioned into specific utility areas, and houses the whole facility's centralised plant: fire services, cooling water (CW), industrial water, emergency CW, compressed air, chlorine gas supply, nitrogen gas supply, argon gas supply, water tower, water treatment, and power transformers and switchgear for Zone 9 itself.

The utility supplies to the process equipment in Zones 1-8 are routed via a pipe bridge from Zone 9 to Zones 2 and 6, and then via internal pipe racks throughout the facility.

External areas

Several facilities outside the main manufacturing buildings support the operation. These include power transformers and switchgear, fume exhausts, waste oil water treatment plant, oil storage tanks, acid tanks, boiler room, and the weighbridge.

Underground utilities include the cable tunnels and associated cable ducts, the stormwater discharge network, foul sewer discharge network, raw water supply, natural gas supply, potable and industrial water supply, and water supply for fire service.

Table 1: Key process equipment suppliers.

	Equipment	Supplier
Zone 1	Melting and holding furnace	Bricmont
	Caster	Wagstaff
	Ingot saw	Alucut
	Scalper	SMS Meer
	Chip conveying system	Kirk & Blum
Zone 2	Roughing and finishing mill	SMS Demag & TMEIC
	Pusher furnace	Ebner
Zone 3	Five-stand cold mill	SMS Demag & TMEIC
	Six-high cold mill	SMS Demag & TMEIC
	High bay store	Siemag
Zone 4	Anneal furnace	China Aeronautical
	Tension levelling line	Herr Voss, SMS Demag
	Wide can slitting line	SMS Demag
	Strip cleaning line	SMS Demag
	Heavy gauge cut-to-length line	SMS Demag
	Light gauge cut-to-length line	SMS Demag
Zone 5	Combo coating line	SMS Demag
Zone 8	Grinder	Herkules
	Grinder	Herkules

10. Pusher furnaces and rolling table in Zone 2 hot rolling mill.

Arup's role

Arup was appointed as both project manager and multidisciplinary engineering designer, including all aspects of project and construction management, architecture, civil, structural, mechanical, electrical, and utilities engineering, and geotechnics for the FRP facility. The scope included scheme design through to detailed design and construction documentation. Because of the local requirement that the client employ an independent company for site supervision ("Jian Li"), this lay outside Arup's scope.

Project programme

This was a fast-track project, and the design and construction were carried out in parallel. As a result, Arup had to develop all the architectural and engineering design from only preliminary process information. As the process design developed, more information, particularly data from the process equipment suppliers, became available. Nevertheless, some elements were built before full design requirements were defined, so the initial design work had to be flexible enough to accommodate continually changing requirements - very different from conventional project design processes. The Arup team was constantly challenged to stay one step ahead to suit ongoing construction demands, statutory approval processes, and changes in the process plant design information, while supporting simultaneous site construction work, by issuing revised drawings at appropriate times.

As a result, the statutory submission and approval durations were a little longer than a "single pass" conventional programme, but overall, project implementation timing was significantly shortened by this multi-stream parallel working approach.

Integrated Arup team

A fully integrated multi-disciplinary team was assembled in house to develop the project design, with the following complementary scopes of work:

- Project management: monitoring and reporting project programme and progress; advising the client on all PM issues
- Architect: masterplanning and building configuration; fire compartmentation requirements; building rainwater drainage; building envelope; internal layout design
- Civil: roadworks, underground drainage systems; underground cables network; underground gas, potable water, industrial water, and fire services mains; waste oil water treatment system; weighbridge; landscaping layout; landscape drainage
- Structural: factory buildings substructures and superstructures; PEFs; water tower; pipe bridges, pipe racks; other structural design input
- Geotechnics: soil investigation; ground treatment; piling works
- Electrical: HV power supply; electrical distribution; lighting illumination; automatic fire alarm; ELV systems, lightning protection, and earthing; electrical supply to process equipment up to electrical take-over-points
- Mechanical: MVAC; fire services; CW plumbing and drainage; steam supply and condensate return; chlorine gas; compressed air; industrial gas; natural gas; industrial water treatment; all utility supplies to process take-over points.

11. The tops of the cooling towers protrude above the roof line.

12. Beige wall cladding and dark blue paintwork are part of the visual language for Industrial City.

Besides Arup, two LDIs were employed: Shenzhen General Institute of Architectural Design and Research (SADI) and Nanhai Power Design & Engineering Co Ltd (NPDI). SADI and NPDI also gave the necessary endorsement of Arup's design work for government statutory submissions and power bureau submissions respectively.

Arup's design work was initially in the Hong Kong and Shenzhen offices but, as the project progressed, the full team moved to a multidisciplinary site office. This allowed quick response to queries from the contractors, the client, and other members of the project team, and naturally fitted the fast-track programme. At the project peak more than 20 engineers from all sub-teams were on site, drawn from Arup's Hong Kong, Shenzhen, Beijing, and Shanghai offices. SADI also provided architect and engineers on site to clarify client and contractor queries.

Architectural configuration

Initial planning

The overall masterplan was dictated by the nine production zones, the process flow, and in particular the vast quantity and size of the associated equipment. The initial challenge was soon identified as the need to begin construction as soon as possible for the client to meet his financial obligations, even though the technical requirements for the equipment in many areas of the facility were not determined.

The critical path to progressing the project was to develop, in close association with the client's operations manager and a limited number of equipment suppliers, the layout sufficient to determine structural grids, column locations, and overall building shell. This enabled a government submission to be made and, soon afterwards, the piled foundations to be started. This fast-track approach inevitably led to some design changes later but there proved to be very few – a testament to careful co-ordination with the client's experienced operations manager.

To facilitate government submission, an LDI was needed to check and sign off Arup's plans. Proposals were obtained, interviews conducted, and SADI was appointed. It was also established that many equipment foundations, some incorporating three-storey basements, would need to be constructed after completion of the main building shell.

Fire safety strategy

Arup prepared a fire safety strategy early in the planning phase to help speed government approval for the masterplan. However, a new set of government requirements was in process of being put in place. Construction of the facility would inevitably be still ongoing when the new requirements came into force and so, to protect the client's best interests, two fire safety strategies were devised and worst case requirements adopted to avoid problems later in the project.

Visual language

The client had a very clear visual language already set up for the whole of Industrial City to create a "family" of buildings. Beige wall cladding with dark blue roof cladding dominated the colour scheme (Fig 12).
The visual intrusion of security fencing was eliminated by incorporating a moat and introducing large landscaped approach areas to help make the working environment attractive.

Amenities

Due to the facility's immense size, 16 amenity buildings serve the staff at strategic locations, thus avoiding unnecessary personnel movement. Each amenity building contains toilets, washrooms, changing rooms, and a rest room equipped with a kitchen. The rest rooms are particularly important for physical relief of the many workers close to extremely high temperatures, particularly in the furnace and hot mill zones. These rooms are on external walls to enable convenient ventilation, visual relief with windows, and in some instances outside access.

The production line is about 1.7km long and takes more than 30 minutes to walk. Unnecessary personnel movement has been eliminated as much as possible not only for productivity but also for safety reasons. Staff have colour-coded passes relevant to their particular zone and are not allowed into other zones.

Transformer room buildings

Over 90 transformer rooms were required for power, primarily to the equipment. These are generally outside the main production facility as the physical dimensions, construction methods, and timing of their construction were different. As is normal practice in China, a power LDI (NPDI) was appointed to advise on all issues related to the transformer rooms for approval by the power supply company.

Emergency vehicular access (EVA)

EVAs run through many of the zones due to the very deep plans, some areas being 150m from the nearest external wall. These routes also provide maintenance access for the operator. With the operator's advice, EVAs and the dedicated fire station were located as close as possible to those items of equipment that are more prone to regular fire breakout.

14. Head office building.

Rainwater system

The operator identified water ingress as an issue of concern, as just a small amount of water on a new aluminium coil can ruin the final product. It was also recognised that the equipment foundations, which were being established on a slower programme, were extremely complex engineering structures – even incorporating a below-ground train/trolley system – and up to 15m deep. In consultation with the client it was decided to avoid where possible an underground drainage system within the building using failure-prone valley gutters, and instead generally discharge roof drainage to the perimeter. This strategy was also adopted in the early phases of Industrial City to good effect. Large robust concrete gutters at the roof perimeter lead to UPVC downpipes connected to the underground drainage system.

External roads circulation/security

The FRP facility has its own security system over and above that provided for the Industrial City as a whole. Two control/security access points are provided, each serving both vehicles and personnel. Card reader turnstyles are provided for staff on foot. All goods vehicles entering and leaving the facility are weighed to control raw materials delivery and finished goods leaving the premises. The vehicle flow, parking, swept path analysis was completed to finalise the detailed masterplan layout.

13. Transformer rooms are generally outside the main production facilities.

Civil and structural design

Arup's main structural tasks were to design the factory building to house production, the structures that support the process equipment and the associated auxiliary equipment, and provide technical input in resolving construction queries on site.

Pipe bridges and racks, cable tunnel

Due to the need to accommodate the large quantity of process pipework, ducts, and utilities for the supply to the process equipment in all zones, elevated pipe bridges and pipe racks were installed to link all the buildings. Their design had to cater to the plant's operational requirements as well as the continuous changes requested by the client and the equipment suppliers. This resulted in numerous design changes throughout the project to revise the arrangement of pipe racks in each zone.

A 4m wide, 2m deep, and 1km long cable tunnel was built to provide power feed to Zone 9.

Factory building

The usual design procedure for a factory building is firstly to collect and understand the design requirements from the client's process design team and the process equipment suppliers, eg machine size, cables and pipework for supplying utility to the process equipment, space requirements for normal operation and maintenance, overhead crane operational requirements, etc. With the data collected and finalised, the layout of the structures supporting the process equipment can then be worked out, and then the factory housing the process equipment designed with particular attention to the profile of the structure supporting that equipment and the other operational requirements. Clearly it would have been advantageous to get the PEF profile before designing the factory building, but the project program did not allow for this.

At the time Arup was engaged as structural designer, the client had worked out a preliminary layout of the factory building based on experience, and this layout was issued to various process equipment suppliers for the design of the process equipment. So major revisions to the factory building layout were not possible. Apart from the preliminary factory layout, the process equipment was still in design by various suppliers and the data were not yet good enough for the structural design. But even though the process equipment layout was not finalised, Arup completed the factory building design using the preliminary layout, and construction began immediately after the design drawings were issued so as to meet the project programme. The factory building design was then continuously amended throughout construction to suit the development of the production process requirements.

Aluminium melts at around 660˚C. The hot mill operates at about 300˚C. One resulting concern in the design was the effect of this heat on the building structure as well as the PEF. Generally heat shielding, like 1200˚C mineral wool insulation and fire brick in the melting and holding furnace, is provided for all process equipment to reduce heat loss and thus minimise energy consumption. Further consultation with the client and the equipment supplier confirmed that the ambient temperature inside the factory building would be around 45˚C, a level safe for conventional reinforced concrete and structural steelwork. It was thus unnecessary to consider the effect of high temperature on the structural material.

15. Pipe bridges accomodate the large quantity of process pipework, etc.

16. Installation of the five-stand hot rolling mill.

Process equipment foundations

The key in designing the structures to support the process equipment was to understand the complex geometry and details of the machines, the delivery strategy for process equipment, the interface requirements between each item of equipment, and the production process in the factory. This was achieved through efficient communication – frequent design workshops with Asia Aluminum's engineers, e-mail discussions with process equipment suppliers from different countries, and weekly internal design team meetings. Design workshops were also arranged at the head office of one principal equipment supplier in Germany. As a result, the process equipment foundation not only met the client's basic requirements, but also coped with the process of equipment installation and allowed flexibility in the final provisions – and has reserve capacity for future extension and maintenance.

Communications were further enhanced by being able to understand the different languages and cultural backgrounds of various parties, which allowed Arup to undertake comprehensive and multilingual co-ordination between the client, equipment suppliers all over the world, and local stakeholders in China.

A good communication/information management system was also vital to success. Basically, it recorded collected data and circulated them to the corresponding structural designers for action, but given the vast quantity – melter data from supplier Bricmont, ingot scalper from supplier SMS Meer, pusher furnace from Ebner, roughing and finishing mills from SMS Demag, fume exhaust from Busch, process pipework design by Asia Aluminum's process design team – managing it was a huge ongoing task. The communication/information management system was further extended to the construction phase to ensure that the correct information went to those concerned, eg to systematise feedback in response to contractor queries.

As with the factory building design, the PEF design was under a tight programme and Arup had to complete it before the process equipment design was fully finalised by the suppliers. After the first round of PEF design was completed, Asia Aluminum's designers and process equipment supplier representatives began to arrive on site, so Arup's full design team was also transferred there to keep a close connection with them. This also provided direct support to the client in resolving construction queries.

17. The effect of loading impact on machinery was critical to the foundation design.

18. The 45m tall high bay store under construction.

One of the main structural design challenges was to design the PEF to withstand the different types of loading – from the equipment's self weight to the 11 000kN of lateral impact if aluminium plate accidentally hits the mill stands. Intensive discussions with the equipment suppliers helped the team understand the properties of these loadings, like frequency of occurrence and points of application. It was also essential to understand the loading presentation method use by the suppliers, who are mechanical engineers and whose presentation can be quite different from what a structural engineer is used to.

Another design challenge was to convert the data from various process equipment suppliers around the world into structural drawings legible by the Chinese civil/structural contractors – another reason why the full design team had to be stationed on site.

There was some concern whether the equipment operation would induce dynamic effects in the PEF, but consultation with equipment suppliers suggested that this would be minimal. For confirmation, dynamic analysis of the PEF was carried out to look at its responses, concluding that the dynamic effect would be minor and could be ignored.

19. Drilling rigs as far as the eye can see.

20. Cavity remedial works.

21. PHC piles for factory foundations.

Geotechnical design

Bored piling

Approximately 1800 1m and 1.2m diameter piles were bored for the PEF. Pre-drilling verified pile founding integrity and at one point, due to the fast-track programme, there were over 70 drilling rigs on site (Fig 19). The pre-drilling was carried out for each pile location with termination criteria of
(1) continuous 10m slightly decomposed rock, and
(2) 80% TCR (total core recovery), to ensure that the appropriate founding level and adequate cap rock were determined. Cavity stability was modelled to study how thick the cap rock needed to be to support the load imposed.

Due to the network of fissures/cavities in limestone bedrock, slurry leakage was common during chiselling. The contractors were asked to submit the cavity remedial work strategy prior to piling, to avoid any ground collapse or sinkhole formation:
(1) For cavities/fissures less than 1m high, the hole should be filled with rock.
(2) For cavities 1-2m high, cement was to be added to the rock when filling the hole (Fig 20).
(3) For >2m cavities, steel casing was added.

Periodic spot-checks were made on the workmanship, quality and site safety of the bored piling works, and post-construction proof tests including sonic logging, full coring, and loading were done in parallel with the works, to ensure quality and shorten construction time. Arup's geotechnical engineers and engineering geologists worked seven-day shifts to handle all design and site issues.

Prestressed high-strength concrete (PHC) pile design

PHC piling – relatively cheap and fast – was used for the foundations of the factories, amenity, and transformer rooms. Over 7000 PHC piles were either jacked or driven (Fig 21). The original design was for 500mm diameter, but after a trial pile test this was changed to 400mm to save cost. In a karstic environment, it is wise not to adopt single or twin pile groups as far as possible, so as to allow redundancy in the pile group capacity. In view of the sharp change from soft to hard layer and the inclined rockhead, Arup advised the client that jacked piling should be used to minimise the number of broken piles. The final breakage rate was around 10% – acceptable for this site geology. Arup's geotechnical team was able to issue replacement pile design changes promptly, though reviewing the piling results and the results from post-construction proof testing, as well as periodic site visits, all constituted a huge workload for the team.

22. Zone 9 utilities on the left, and Zone 6, package and shipping, on the right.

Ground improvement works

In view of the huge area of site formation works and the tight construction programme, Arup introduced an innovatory technique for the ground improvement works to minimize settlement. This, the high-vacuum densification method (HVDM), combines vacuum suction of groundwater and dynamic compaction (Fig 23), so that a hard shell forms in about a month with high-consolidation settlement.

Post-construction proof tests, including SPT, CPT (cone penetration test), and plate load tests, were done to assess the soil parameters and site performance. The cost is around 30% less than conventional methods like cement mixed pile, stone column, vacuum and preloading, etc.

23. Ground improvement works in progress.

a.

b.

Electrical design

The electrical engineering design involved the following systems: main supply, site distribution, site lighting, site lightning protection and earthing, CCTV, broadband, public address, and automatic fire alarm and detection.

Electrical supply and distribution

The 10kV power supply network is directly fed from two 110/10kV 63MVA transformers in the Lui Zhong 110kV station on the east side of the plant), fed in turn from two separate power grid 110kV sources. A third 110/10kV 63MVA transformer is planned for the future development. The 110/10kV station on the west side of the plant, which primarily serves the existing extrusion facilities, has 30-40MVA spare capacity so that it can be an alternative power source for future expansion. The total installed capacity of the FRP Phase 1 is around 180MVA.

Each 110kV power transformer is connected to a 10kV switchboard with 12-way outgoing feeders to supply electrical power to several 10kV substations, which are distributed in multiple load centres to serve different zones (both process and E/M field equipment). The two transformers and their associated 10kV switchboards are considered as two power sources (A and B) for the FRP's supply. A harmonic management centre is also incorporated in the 110kV station. Source A feeds Zones 1, 2, 7, and 8, while Source B serves Zones 3-6. A and B jointly serve Zone 9, with changeover facilities so as to maintain operation of critical utility systems.

The 10kV power distribution network is radial. A radial circuit configuration is also designed into the LV power distribution network.

Fluctuation in electrical loading associated with large surge spikes from process equipment was the major design challenge. The arrangement of transformers amongst different 10kV circuits needed to be closely co-ordinated so as to balance the loading profile on individual 10kV feeders and minimise harmonic feedback to the power sources.

Lighting systems

Architect-designed translucent plates optimise daylighting and thus reduce energy consumption for artificial lighting during daylight (Fig 25). The factory lighting and external road lighting are generally controlled by timers and photosensors, the appropriate light sources being switched on either to a designated time schedule or when the ambient light level drops below a certain level.

Earthing system

The earthing for the electrical systems uses the many reinforcement cages in the building piling as the earth network. Artificial earthing meshes are provided to enhance performance in certain areas, and earthing networks in individual zones are interconnected to form a complete earthing system grid. The lightning protection and earthing systems also are electrically interconnected.

A separate clean earth is provided inside the buildings for grounding designated equipment, through an artificial earthing mesh outside each 10kV substation to serve the corresponding zone. The clean earthing system is electrically separated from the lightning protection and earthing systems to ensure safety and security.

As the Industrial City is in a high lightning strike area, all design and installation of lightning protection systems had to be co-ordinated, reviewed, and inspected by the local government Lightning Protection Bureau.

CCTV, broadband, public address, and fire

The CCTV system provides 24/7 monitoring, surveillance, and recording facilities at all strategic locations including the finished product store and main site entrances and exits. This is in addition to the separate process-dedicated systems included in the turnkey process installations.

The sitewide broadband system comprises broadband router, access controller, firewall, fibres switch, and hub switch connected to the internet services provider. The FRP also has a full public address (PA) system, including zone selector panel, amplifier, voice recorder, call station, volume control, channel selector, digital pre-recorded announcement unit, and loudspeakers; the system can programme message inputs at different priority levels. The local PA broadcasting is overridden when fire is detected and alarm sounders activated. In some areas with high background noise, visual alarms are provided to alert workers inside pulpits and within the control room.

The dedicated addressable fire alarm and detection system (AFA) comprises: (1) main control panel at the fire services control room in the utilities centre; (2) dedicated local AFA control panels in Zones 1-8; (3) manual call points and alarm bells; (4) addressable smoke detectors at electrical plant room/control room/mill room; (5) addressable heat detectors at mechanical plant room; (6) visual alarms to alert workers in the noisy working areas.

24. Nitrogen gas storage tanks.

25. Maximum use of daylight ensures reduced energy use.

Mechanical engineering design

The major systems are as follows:

- compressed air plant with total capacity of 102 000Nm^3/hr and distribution system to the process connection points
- process "non-contact" (indirect heat exchange with the process) CW plant with 120MW total cooling capacity and distribution for cooling to process equipment
- process "contact" (direct heat exchange with the process) CW plant with 70MW total cooling capacity and distribution for solidification of melting aluminium to ingots
- steam generation plant with a total capacity of 10 000kg/hr, supply to and condensate return system from the process connections
- industrial gases including natural gas, CO_2, nitrogen, chlorine, and argon; plants and distribution systems to process connection points
- fire services equipment including internal hydrants, street hydrants, local deluge subsystems, automatic sprinklers, local gas fire suppression systems, and automatic fire detection and alarm; hot (and cold) rolling mills are very susceptible to fire hazard due their use of combustible coolant materials, so fire detection and suppression are vitally important.
- industrial and potable water plants and distribution systems
- mechanical and natural ventilation systems for the plant, and air-conditioning systems for the operations, control, and electronic equipment rooms in plant areas.
- water treatment system for the supply of process CW, industrial water and boiler make-up water, with a maximum consumption of 150 litres/sec.

Highlights of experience gained

At inception stage

Identification of process connection ("take over") points for all the various process equipment items.

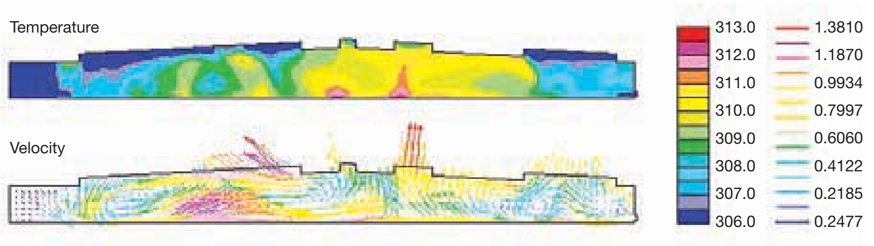
Each production zone contains a wide variety of large-scale process equipment, every item of which requires different types and capacities of services provision (CW, compressed air, various kinds of industrial gases, steam, etc). Through painstaking interviews, Q&A sheets, and numerous meetings with all the key process suppliers, Arup collected and collated all the key technical information for each process installation along with the associated take-over points.

This was consolidated into a database for design information, a crucial resource in designing the system and plant capacities, plantroom sizes, and diversified loading profiles. After identifying the location, quantities, and technical requirement of all the take-over points, Arup tabulated this information on drawings so that all the parties involved, especially the process equipment suppliers and the client's in-house process engineering team, used the same data in developing the process systems design.

Preparation of design proposal

In the inception stage, Arup prepared proposals with various design options for the client's consideration so as to achieve consensus and ensure that the design approach was feasible functionally, technically, and financially. Design notes on each different system in both English and Chinese defined all the design requirements/criteria/assumption/calculations methodology, provided details of any further studies, and then formulated design proposals to meet those requirements. These documents proved essential in assuring design conformity, as they gave the design basis for each mechanical system to be followed during subsequent stages of this project.

26. Computer modelling to facilitate natural ventilation design of industrial plant.



27. Roof ventilation on completed building.

Integration of design concept with other design teams

Close interdisciplinary working was vital for this project to meet the programme. A good example was in developing the design solutions for the centralised utility building (Zone 9) plant areas. These were presented with fully integrated building fabric, structural, and services requirements on consolidated integrated drawing sets to indicate physical dimensions and constraints.

At design stage

The Arup team conducted a range of analyses to verify and optimise the design, for example:

Pipework

The pipe-bridge/piperack provides structural support for the E&M services distribution, so the pipework's dynamic forces and thermal expansion were analysed to ensure that the structural team accommodated the resultant loads into the structural design.

Natural ventilation

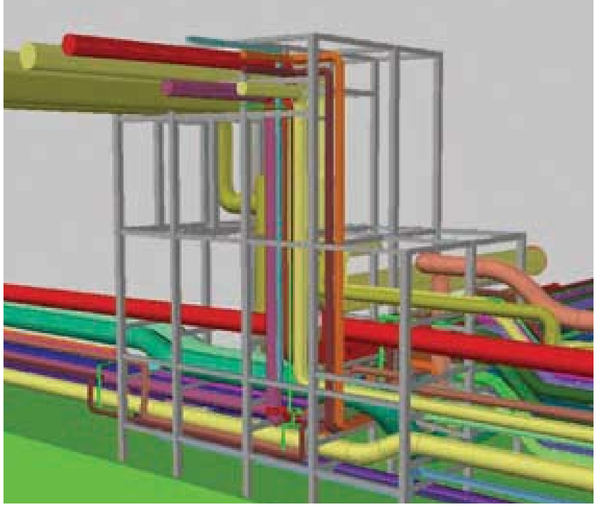
The team developed a natural ventilation scheme, based on the thermal performance of the process equipment and the building configuration. Successful implementation of this approach requires the architectural planning to be considered, particularly the siting of roof ventilator exhaust outlets and side wall air inlets.

Performance is also affected by building orientation, and so analyses of the thermal environment and the building occupants' comfort perception were needed. Dynamic thermal modelling and computational fluid dynamic (CFD) techniques were used to predict the potential environmental conditions (Figs 26, 27).

At tender stage

Arup was responsible for preparing the tender packages, with all drawings and specifications bilingual (English and Chinese). During this stage, Arup liaised closely with the cost manager and PM team to define the contractual and tendering procedures required to meet time and cost restraints, as well as the appropriate form of contract.

For tendering purposes, the E&M systems were divided into 13 packages, an arrangement due to the qualification requirement of contractors in China; some of the E&M system installations such as chlorine gas, industrial gases, natural gas, steam, compressed air, etc, require a special license or recognised qualification from relevant Chinese Government authorities. This ensured that all the contractual packages were tendered by more than one eligible tenderer, as well as allowing a high degree of commercially advantageous flexibility for grouping various packages into a single one.



28. 3-D images of co-ordinated pipelines and structural support design.

At construction stage

To assist fast-tracking the main piping networks installation, Arup supplied 3-D models and associated images to the contractors in the form of a fully integrated reference model, giving the contractors clear illustration of the routing of pipelines, the spatial arrangement, and the associated structural supports (Fig 28).

Project management

The initial project set-up/organisation was a loose hybrid of competing interests, and the client became concerned with lack of progress. The initial project set-up, although not necessarily unusual in China, had several unorthodox elements that conflicted. These included:

- very early appointment of the main contractor when only limited design drawings were available
- conflicting design and approvals interests
- under-appreciation of the complex technological constraints and requirements inherent in aluminium production
- slow progress on key design elements
- slow construction progress.

Arup offered the client ways to improve the project progress and set-up by providing consultancy and professional advice – with due consideration for the project hierarchy. Major roles include recommendations on enhancing the procurement approach, managing workshops and meetings for problem-solving, and covering the interests of client, consultants, contractors, and suppliers. Other key tasks included protecting the client's interests during tender assessment; closely monitoring contractors' resources, programme and progress; managing the statutory inspections approval/handover processes; and overseeing the certification of all critical payments for protecting both client and contractors' interests.

To implement and monitor this process a key core group of more than 10 management staff were deployed to the facility. They were tasked with developing the following project control systems.

Communication and Information management

A key feature of Arup's PM services lay in maintaining close communication with all project stakeholders; in particular, dialogue with the contractors and stakeholders, reinforced with a continuous site presence. Minimising communication gaps between different stakeholders through proper information flows was also important to encouraging a culture of success.

The initial contractor employed up to 64 sub-contractors. Following his replacement, and with the assistance and co-ordination of the PM team, an additional 154 sub-contractors and specialist suppliers were sourced (not including all the specialist suppliers and process equipment installers involved during the installation stage). With so many sub-contractors, maintaining effective communications was a necessity, and the PM team spent nearly a month developing proper information flowpaths for all matters that required better communications. This included numerous meetings, design workshops, and high-level meetings with the client.

Problem-solving workshops, whether for design co-ordination, construction co-ordination, or value management, formed one of the PM team's resources in optimising solutions. These served as a way to quickly generate design solutions while integrating the aptitude and interest of a diverse group of people. They also eliminated any risk of surprises for stakeholders downstream of the process.

To further improve this mechanism, the PM team managed a series of workshops, meetings, interactive activities, short sessions and data lists with individual stakeholders, with the aim of ensuring that all could understand the project requirements and identify the barriers to and potential risks for completing it.

Partnering approach

The PM team spent over a year facilitating the series of workshops and meetings for all different stakeholders to clearly identify their roles and clarify their shared purpose and direction. Of particular importance was the nature of the relationship between the PM team and the main contractor, who was appointed as the management contractor.

With so many nominated subcontractors, many meetings with each were required to develop the control mechanisms that were needed to ensure that the interests of all parties were fairly considered and common project objectives achieved.

Arup's PM team monitored these meetings, ensuring that all critical issues were discussed and covered, and by keeping the meetings short and concise, focus on key points was maintained. The PM team proactively worked with all key individuals in developing solutions.

29. Pipe bridge for supporting services pipeworks connected to the factory buildings.

By showing sensitivity, in conjunction with clear lines of demarcation between what was and was not acceptable, the team also gained trust and respect from the client, main contractor, subcontractors, and other parties by tackling daily issues in a just and impartial manner. The PM team crucially helped to resolve issues that initially seemed insurmountable but proved, with support and direction, to be capable of amicable resolution.

The project's sheer scale involved many cultures, languages and beliefs. Developing a partnering approach helped to bring this diverse background of people together in a successful partnership.

Resource management

A major element in project management is managing people, and the PM team provided overall monitoring of the project as well as direction to its development. To ensure all development was controlled and progressed as intended towards the ultimate goal, the team:

- provided support to the client to meet his requirements and project objectives
- understood the ultimate goals of all participants: stakeholders, consultants, and contractors
- understood the different priorities of the various team players and helped them resolve conflicts when they arose
- developed communication channels to manage the information flow
- understood the needs and constraints of the various team players.

Because of the size of the project, it was critical to the overall progress that adequate resources should be in place at its successive stages.

The PM team closely monitored contractor resources to ensure that all the works in each zone at each stage were well planned and covered. China's ongoing construction boom means that labour can be in short supply, and especially during some long national holidays the PM team required the contractor to plan ahead and work out manpower scheduling to meet the project programme.

Programme management

The extremely tight schedule made a just-in-time strategy in co-ordinating cross-over site activities crucial to saving project time and cost. The PM team reviewed and delegated the main contractor to take the lead role in site co-ordination, planning ahead on work sequences and the delivery schedule of heavy loads of materials to site so as to reduce and avoid redundant and abortive work.

Procurement management

The PM team oversaw the tendering assessment processes and the certification of all critical payments, as well as the statutory inspections approval and handover of each zone to the client.

Completing the project involved a vast number of subcontractors, specialist suppliers and process equipment installers with different cultural backgrounds and local practices. On the client's behalf, the PM team also helped to clarify and monitor the scope of works of every contractor to ensure that all the required works complied with the international standards required, were not left unattended, and that their completion timelines would not significantly affect the agreed milestones.

Cost management

To achieve value for money, the PM team encouraged the contractor to offer alternatives for improving project cost and progress, as well as overseeing the appointment of a quantity surveyor to administer the contract with respect to contractual claims assessment. The team also offered periodic consultancy and professional advice for revising the project hierarchy, and even advised on restructuring the client's team for the process equipment installation. Arup's PM service contract did not in fact include the installation works, and thus the team went beyond its scope in pursuing the client's best interests. China's construction boom made fluctuations in materials costs a serious issue, and the PM team helped the client to resolve this through meetings with the main contractor and subcontractors.

Risk management

Risks were ever-present throughout, and as project manager, Arup initiated stage workshops to review potential risks, identify problems, and make contingency plans to mitigate or reduce their effects. If, for example, a contractor was performing unsatisfactorily and the progress of installation works would adversely affect the target completion date, workshops were arranged with relevant consultants and contractors to develop an alternative solution to resolve or mitigate the problem. The PM team's constant monitoring of progress kept the client abreast of all potential risks throughout the project at different stages. Specialist risk management, technical, and managerial advice was available to the client whenever critical decisions had to be made.

Innovation

Though part of the cold mill comprises refurbished existing equipment from plants in the USA, much of the process and production line equipment is among the most advanced and high-end of its kind in the world. The structural loading requirements of the major items of equipment are non-typical and non-uniformly distributed.

30. Rear elevation of the office building.

31. Water storage tower and utilities building.

There are also very high dynamic loads, which led to considerable challenges in the design of the highly complex machine foundations. The utility supplies to the process equipment require high purity (and large volumes of) CW, large quantities of compressed air, and very considerable (but fluctuating) power consumption. In order to balance utilisation, the Zone 9 utility area was designed to house centralised utility plant and supply equipment.

Optimising both natural ventilation and daylighting supports energy-efficient operation.

Collaboration

Generally, the client provided Arup with process plant information, such as individual equipment positions, dimensions, and weight, precast bolt requirements, embedded containment routing, control room specifications, MEP utilities requirements, etc, and then individual teams began design of provisions for the plant. Information had to be exchanged between these teams to enable detail design review and co-ordination.

For example, the E&M team supplied utilities routing and equipment plinth data so that the architectural, civil, and structural teams could make appropriate provision; the architectural team gave control room design information to the structural and E&M teams for their corresponding designs, and the structural team exchanged foundations requirement information with their geotechnical colleagues. If a conflict occurred, eg E&M utilities routing with a structural element, possible solutions were immediately discussed.

Additional challenges came from the fast-track nature of the programme, changes to the process plant design, operational constraint requirements, contractors discovering restraints during construction, etc. All these required the design to respond and adjust quickly to suit the latest information and requirements, and meet the construction programme. In such a design process, it was vital that the various Arup design teams had strong co-ordination and communications to maintain smooth delivery of the works.

Conclusion

The Asia Aluminum FRP project in Guangdong is a notable success story for Arup. It is the largest aluminium rolling mill in China, on a challenging site, and with multiple equipment suppliers and contractors. There was already a design team in place, from which the client desired Arup to diplomatically extract the project and deliver it to an acceptable level of quality (in China), within a tight budget, in three years from a standing start. Arup ensured that the site investigation was properly performed, the ground remedialised, the foundations installed, and the superstructure erected, while simultaneously getting highly detailed geometric and dynamic loading data from Canadian, Chinese and German suppliers. Both the hot and cold mills were installed effectively at the first attempt with no rework. All this was done without the aid of either physical or virtual models, and for a client who had never built or operated such a facility ever before.

Reference

(1) GENERAL ADMINISTRATION OF QUALITY SUPERVISION, INSPECTION AND QUARANTINE. *GB50108-2001*. Technical code for waterproofing of underground works. Ministry of Construction of the People's Republic of China, 2001.

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Credits

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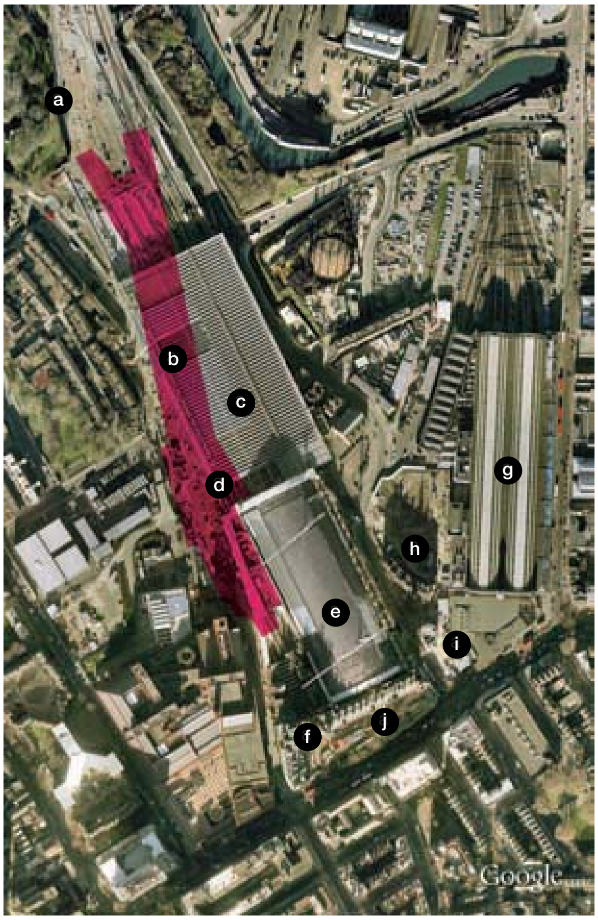
1. Mezzanine level above the main domestic concourse.



2. Aerial photo showing: (a) enlarged embankments; (b) Thameslink junction and station box; (c) deck extension for HS1 trains, Midland Main Line and Heathrow Express; (d) new Thameslink station; (e) St Pancras International; (f) refurbished St Pancras Chambers; (g) upgraded Kings Cross station; (h) new northern ticket hall; (i) upgraded existing ticket hall; (j) new western ticket hall.

The Thameslink station at St Pancras, London

Adam Chodorowski Martin Gates-Sumner

"This new station will improve the daily journey to work for thousands of passengers. It means that we can tackle overcrowding and deliver longer trains under the Thameslink modernisation scheme".

Ruth Kelly MP, UK Transport Secretary

Introduction

Arup's work with its partners Bechtel, Halcrow and Systra in the consortium Rail Link Engineering (RLE) that designed and project-managed Britain's High Speed 1 (HS1, formerly CTRL, or in full, the Channel Tunnel Rail Link) was summarised in 2004 in a previous *Arup Journal*[1]. Many individual projects were involved in the entire scheme. One not included in that edition was the new station beneath St Pancras International for Thameslink, the 50-station London commuter rail network that extends from Bedford, some 90km miles north of the capital, to Brighton on the South Coast.

The original brick-lined railway tunnel that carries today's Thameslink route passes under the footprint of St Pancras International, and a new station here for Thameslink, able to accommodate up to 24 12-carriage trains per hour and provide a connection to the East Coast Main Line (ECML), was always seen as a necessary part of the long-planned Thameslink 2000 upgrade project. The major construction works at St Pancras presented the opportunity to build an underground structure on the route of the existing tunnel, and provide a direct passenger interchange with the international station (Fig 2). Two new tunnels were also constructed, forming a potential connection to the ECML route.

The new rail infrastructure in the St Pancras and King's Cross Lands area is one of the most complex parts of the whole HS1 project. The interface between different elements of the works and external parties here required careful planning and design to ensure that the different phases of construction from 2001 to 2007 could take place safely with minimum disruption and delays.

One structure which exemplifies the issues and constraints of construction at St Pancras is the Thameslink box, the detailed design and planning of which required close collaboration between the client, project manager, designer and contractor, as well as a clear interface with external parties including the local authority and residents.

This important piece of infrastructure is an integral part of the overall transport interchange at King's Cross/St Pancras. The Thameslink box was successfully built within a 35-week closure of the Thameslink route, which was reopened to through trains on 20 May 2005. The box contains the new Thameslink station and provides connections between the existing and proposed Thameslink routes currently operated by First Capital Connect. After being fitted out, the new Thameslink station opened for public service in December 2007.

General layout

Wholly underground, the box is some 380m long, nominally 22m wide, about 12m deep, and can be divided into the following areas (Fig 3):

- 250m long station platform area
- 100m long track junction area
- 30m section (the "trouser legs"), connecting to the existing Thameslink tunnel and the new tunnels to the ECML route
- plantrooms
- east and west central concourse areas
- northern emergency exit area
- southern emergency exit and ventilation shaft.

The central areas are built around the existing shallow Victorian brick arch tunnel carrying the Thameslink railway. A 26-week blockade period for the main construction was originally planned, during which the through Thameslink services would be terminated and the existing tunnel at this location demolished.

In addition, the Fleet sewer, which crossed the site of the box, had to be diverted without disruption, as were many other services including the twin 900mm diameter gas mains that are an important supply to north-west London. The Fleet relief sewer runs immediately beneath the box and constrains the structure's depth, as does the deep Thames Water ring main, locally restricting the toe level of the piled construction.

The railway tracks are about 10m below ground level, and three internal pedestrian overbridges and two structures carrying the diverted Fleet sewer and gas mains all cross the tracks. These restrict headroom above rail level, requiring a reduced height overhead electrified line configuration to power the trains. The roof of the box supports Midland Road, Pancras Road, and a significant part of the new St Pancras station extension.

Ground and groundwater conditions

Ground investigations by RLE in the St Pancras area confirmed the site's geology (Table 1). The various stages of development over the last 200 years had left behind buried foundations, backfilled brick viaducts, and deep redundant gas holder tanks on the east side, with the old St Pancras Church graveyard and its numerous remains at the northern end of the site. Natural buried features include the course of the original Fleet River.

The groundwater level was found to be close to existing ground level, with a hydrostatic groundwater profile to about -12m OD. Beneath this level, groundwater pressures have reduced due to historical water abstraction in the underlying chalk aquifer, and the anticipated future long-term rise in groundwater level in the deeper soils was taken to be 10m OD.

3. Principal elements of the Thameslink station and box.

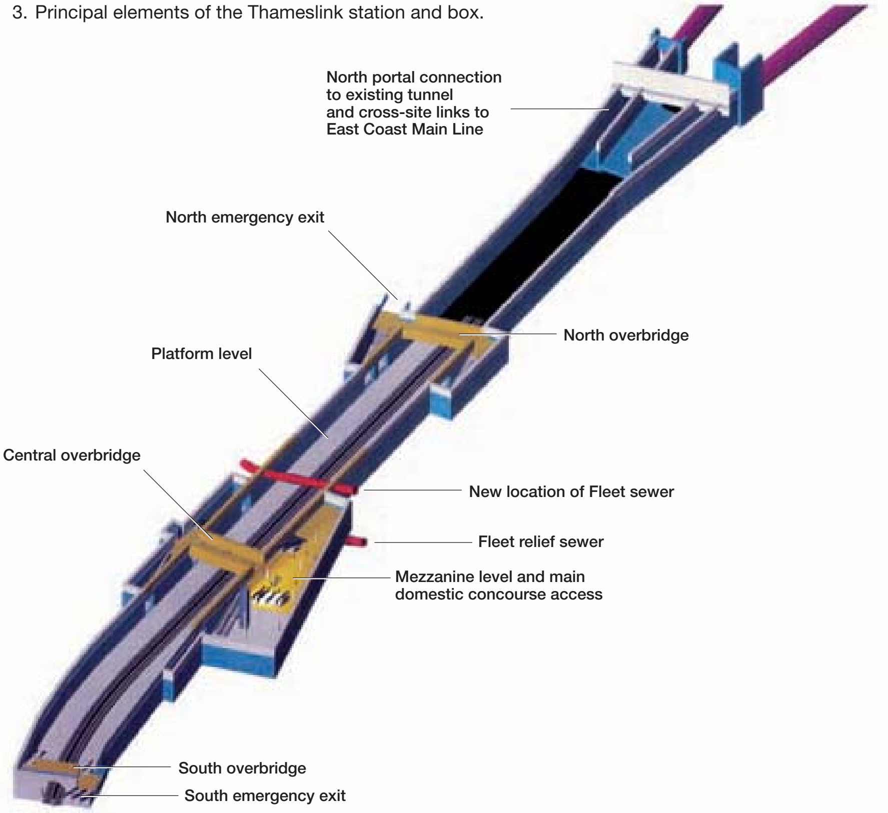


Table 1. Site geology.

Stratum	Thickness (m)	Level of top of stratum (mOD)
Made ground	1-7	17-22
Alluvium	0-2	13
Weathered London Clay	1-4	12-15
London Clay	12-14.5	9.5-12
Woolwich and Reading Beds	10-13.5	-1 to -2.5
Upnor Formation	5-6	-15 to -17

Note: Woolwich and Reading Beds and Upnor Formation are now classified as the Lambeth Group.

External constraints on the works

The construction site is next to a housing area. Relationships with the residents and Camden Council had always been constructive and supportive, but the initial Thameslink station excavation and demolition proposal – an open cut-and-cover construction 24 hours a day for the entire 26-week railway closure – met with outright objection. After much negotiation and compromise by all parties, the works were replanned over 35 weeks with the agreement of Network Rail and the train operators. The box roof was to be built first, forming a noise shield to allow excavation and demolition of the old tunnel to be carried out as a mining operation.

At the northern end of the box it was necessary to remove and re-intern off site an unexpectedly large number of burials from the remains from the old St Pancras graveyard. This required extended and sensitive work by a specialist contractor, leading to delays in the programme.

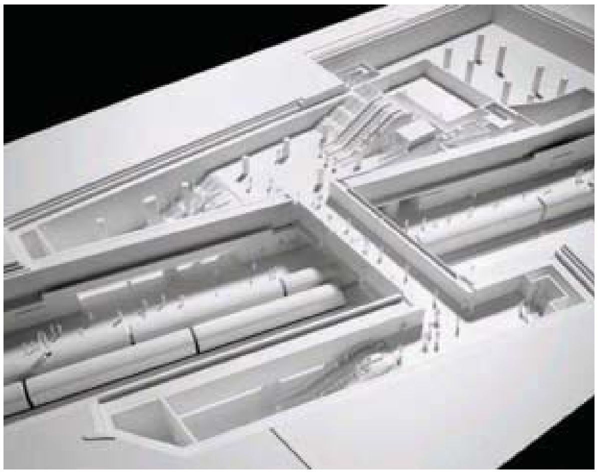
Value engineering and buildability studies

Before detailed design began, RLE (including Arup) and the joint venture contractor Costain O'Rourke Bachy Emcor Rail (CORBER) jointly carried out value engineering and buildability studies during late 2001 and early 2002. Several different schemes for the complete box and individual components, in terms of technical and construction feasibility, were studied, with the aim of reducing costs and the risk to programme, particularly during the planned blockade.

In June 2002 the team proposed the following solutions to the client, Union Railways (North):

- contiguous bored pile retaining walls with shotcrete infill (apart from sections adjacent to the dismantled gasholder tanks where secant pile walls were used)
- isolated piles with plunge columns at concourse entrances
- under-slab drainage
- corbel connection between the base slab and piled wall
- top-down construction using a single level of propping action with groups of four permanent precast roof M-beams at 15m centres
- use of an intermediate level of temporary steel props for a short section adjacent to the existing St Pancras train shed (Barlow shed).

4. Architect's model of the Thameslink station.



The team decided not to adopt the Observational Method* for constructing the box, considering that certainty of performance in the design and construction of the different elements during the blockade period was more important than any potential savings. This was emphasised by the substantial cost for each day's delay in handing back the reinstated railway.

A task force of design and construction engineers was subsequently assigned to develop and optimise the box roof design, taking account of the interface with the deck extension above. In November 2002, agreement was reached for the roof's detailed design basis, including:

- steel plate girders at 15m centres to suit an optimised deck extension structural grid
- bearings at the steel plate girder supports
- elastomeric bearings for the M-beams support
- a pin connection between the roof structure and the retaining wall
- propping action for the box walls provided by the M-beams only
- flat slab construction in the east and west central concourse areas
- movement joints with suitable waterproofing details in the roof structure.

These items further de-risked the overall programme and enhanced the potential savings. More value engineering and buildability studies were examined and adopted during the detailed design.

Detailed design

Detailed design of the box retaining walls and capping beams began in June 2002 by a dedicated RLE/Arup design team in the JV contractor's office. Being co-located there enabled the basic principles of the construction sequence and reinforcement detailing to be agreed, with critical items prioritised, potential problems identified, and solutions reached quickly and efficiently.

Finite element analyses with Arup's OASYS program *SAFE* were used to model the excavation, develop an optimum design for the base slab, and predict the loading and deflections from long-term heave swelling of the London Clay. Different arrangements of under-slab drainage, with and without compressible layers, were considered.

For the central box area, a ground-bearing slab was used, with a drainage layer of no fines concrete and a void created by a proprietary plastic dimpled form together with overflow outlet and inspection pipes cast into the slab. Because of the restriction on piling adjacent to the existing tunnel, it was not feasible to construct, before the planned blockade, internal piles within the central box area to restrain the base slab; construction of internal piles could not be accommodated within the blockade.

Elsewhere, the base slab comprises a ground-bearing edge strip adjacent to the bored pile wall and a suspended slab with compressible and drainage layers. An inspection and maintenance plan for the under-slab drainage was developed to ensure that the system operates effectively during the 120-year design life.

A more complex 3-D finite element model using *DYNA 3D* was set up and analysed by Arup to predict the behaviour and interaction of the box construction plus the new deck extension plus the adjacent Barlow shed with its brick abutment side walls and wrought iron tied arches. This proved an important tool for the separate design teams having to deal with the complex interaction of these structures. It also provided trigger values for subsequent movement monitoring during construction.

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* The Observational Method is a construction process developed by Prof Ralph Peck where the design is based on most probable parameters with monitoring during construction to confirm the performance of the structure and agreed mitigation measures developed on a parallel design using moderately conservative parameters.[2]

5. Escalator and stair link from mezzanine to platform level.

Some of the initial value engineering ideas were extremely positive. For example, the adoption of contiguous bored piles resulted in much simpler reinforcement cages, although secant bored piles were still required in the north-east area where the box intersected with backfilled gasholder tanks.

The use of the corbel was also a good solution as it could be constructed after the base slab and was not a critical path activity. It also facilitated unrestricted construction of the base slab and enabled prefabricated reinforcement cages to be used. However, other ideas such as base slabs with varying thickness were not adopted as the practical aspects proved more difficult than initially expected.

Reference rail alignment

The contract originally specified that the railway within the box was to be reinstated to the existing alignment. However, the alignment in the existing tunnel was found to have a sub-standard 1.83m clearance and did not suit the arrangement for the proposed station. RLE produced a reference design for the rail alignment that optimised the track position in relation to the tracks in the existing tunnels at the ends of the box. It also gave acceptable reduced vertical clearances beneath the new footbridges and Fleet Sewer diversion and a satisfactory configuration for the proposed station. The reference alignment was for plain line twin tracks through the box. The switches, crossings and turn-outs for the Thameslink railway into the new tunnels connecting to the ECML will be carried out by Network Rail at a later date.

CORBER's railway engineers adopted the reference alignment for the reinstated railway's detailed design, as did the RLE/Arup engineers for the detailed structural and civil design of the box. The Thameslink station fit-out team also used it to plan and design the platform areas.

Revised design to suit programme constraints

Towards the end of 2003 it became clear that programme constraints required some significant revisions to the design so that construction elements could be brought forward and critical target dates achieved. These, together with some value engineering ideas, included:

- revised top-down construction of the CTRL plantroom and east central concourse
- relocation of the temporary gas main diversions
- re-detailing the roof M- beam propping arrangements
- casting a post-tensioned concrete roof slab at Pancras Bridge Road
- redesign of the base slab reinforcement to allow use of part-prefabricated reinforcement cages.

To ensure that design information was delivered in time for construction during the planned blockade in late 2004, the revised design was agreed to be split between RLE/Arup and CORBER, the latter taking over design of the top-down construction. This required very detailed consideration of the deck extension built over the box plantroom and east central concourse areas, and included design and procurement of steel plunge columns with temporary bearings.

Construction

The site area of the Thameslink box was constrained by the overall phased construction at St Pancras. Piling and capping beam construction had begun in late 2002 at various locations as areas became available, and this was largely completed by the start of the blockade. Demolishing the existing viaduct, and top-down construction in the concourse and plant areas, could only start after transfer of the Midland Main Line services out of the Barlow Shed in April 2004. Thus the total site was not available until May 2004, after which the blockade began in September and lasted 35 weeks until May 2005.

The contiguous bored pile retaining walls are 1.2m in diameter, between 25m and 34m deep, and set into the London Clay (Fig 10). The deepest tension piles and deep plunge column piles with toe levels generally deeper than -10mOD were constructed using polymer drilling fluid to counteract the increased water seepages from the sandier Woolwich and Reading Beds below this depth. The contractor chose to use polymer here as it could be reused more easily and disposed off-site more economically than bentonite. Pile reinforcement cages constructed of 40mm and 50mm diameter high tensile steel reinforcement bars with coupler connections were fabricated off-site because of space constraints, and delivered to site when required.

The west central concourse, north-west emergency exit, and Fleet sewer diversion were also constructed before the blockade, as were large sections of the roof M-beams and the post-tensioned slab at Pancras Bridge Road.

Groups of 4 M-beams at 15m centres bearing on the perimeter capping beam were used as a single level of propping for the box piled walls, with openings for construction access between the groups. An intermediate level of temporary steel props was installed for a short section close to the Barlow Shed to further limit lateral movement of the ground in this critical area.

From the start of the blockade the box excavation, including demolition of the brick arch tunnel, was carried out on three work fronts.

Firstly, spoil from site was classified, segregated, and removed by lorries to a railhead at the King's Cross lands. Secondly, the base slab was constructed using partially prefabricated reinforcement cages in approximately 10m bays. Thirdly, a crane gantry system suspended from the box roof moved reinforcement and other materials from openings in the roof structure to the advancing work sites in the box. The cycle of base slab construction was about five days.

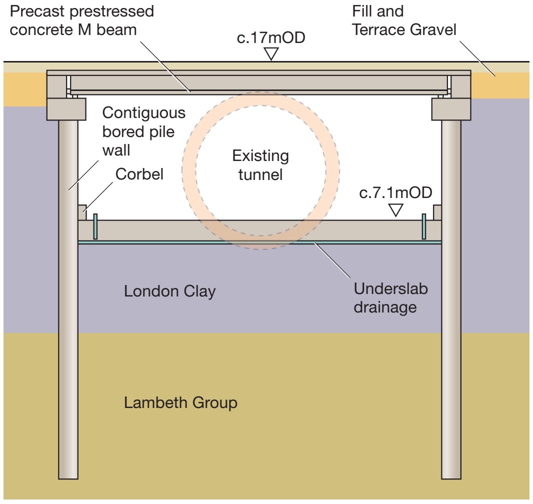
The steel plate girders were fabricated off site, transported in overnight, and placed directly onto bearings in their final locations as soon as a section of the existing tunnel had been demolished.


6. Construction at the south end of the box, October 2004.


7. Roofing the box opposite St Pancras platform extension, October 2004.


8. Excavating main Thameslink station area, October 2004.


9. Track laid in main station area, March 2005.



10. Section through Thameslink box.

Monitoring horizontal deflections of the bored pile wall and prop loads at critical design sections confirmed that the cut-and-cover structure was performing well within the predicted values, with wall deflections generally less than 10mm compared to the maximum prediction of 25mm. The loads measured in the concrete beams and temporary steel props were generally just below the maximum predicted values. The Barlow shed was also monitored as the box excavation progressed, and the movements and increase in its roof arch tie forces were all less than predicted.

The civil engineering works were completed and handed over to the railway sub-contractor in good time for reinstatement of the railway track, electrification and signalling systems. Trains recommenced running through the now-completed structure on 16 May 2005 with the remainder of the internal works being completed behind safety screens. The completed Thameslink box structure was handed over for fitting-out in December 2005.

Station fitout

The original intention was for the HS1 project to complete the structural works for the Thameslink station and hand it over to Network Rail for its completion as part of the Thameslink 2000 project, but delays to approval and funding of the latter prevented this. However authority was obtained to fit out the Thameslink station as part of the St Pancras works so that it could be completed and opened at the same time as St Pancras International. RLE and Arup designed the architectural finishes and mechanical and electrical services to Network Rail's approval, and procured contractors to carry out the works. Network Rail modified the track and signalling to permit trains to call at the new Thameslink station, and decommissioned the old Thameslink station at Kings Cross.

The new station has two 250m-long platforms, each with a central access/egress point connected by a wide mezzanine-level overbridge. Escalators and stairs link each platform to the central mezzanine concourse, from which a single bank of escalators and stairs rises into the ground-level Thameslink concourse. Both platforms have lifts to mezzanine level, suitable for use by mobility impaired persons, with the lift on the southbound (east) side of the station extending up to ground level. Overbridges and escape stairs at the end of each platform provide direct egress onto Midland Road, and there is a firemen's access stair in the central concourse.

The station was designed for 12-car trains arriving and departing at up to 24/hour in each direction throughout the three-hour am and pm peak periods when the full service is operating, with total flows at these time of some 18 000 passengers. At opening, the demands were less, with eight-car trains operating at up to 18/peak hour in each direction, and the station handling up to 4000 passengers/hour.

The passenger flow program *PAXPORT* was used to model the safe movement of the public through the station in normal, perturbed, and emergency scenarios. The impact of delays to the planned service of five and 15 minutes was tested, as well as the effect of a breakdown in UTS (underground ticketing system) gates and of one escalator taken out of use in the two banks of them between platform, mezzanine, and ground levels.

Evacuation measures

In an evacuation, the target times agreed with LFEPA (London Fire and Emergency Planning Authority) were four minutes for passengers to clear the platforms and six minutes to reach a place of safety (the ground level concourse). An extension to these targets of up to one minute was successfully presented to and accepted by Network Rail and LFEPA for the worst-case scenario required by HMRI Railway Safety Principles and Guidance (RSPG) – a five-minute delay to the service with a crush-loaded 12-car train arriving on fire at a crowded platform. The travel distances for the primary escape routes significantly exceed the normal 45m dual route limit for a place of assembly, but the application of fire engineering principles made this acceptable in accordance with *BS5588* Part 6[3]. Glazed downstands at the platform exits, and discrete smoke reservoirs formed by the box overbridge structures (Fig 11), enabled mechanical smoke extraction from these to be used as primary mitigation for the extended travel distances and escape times. Computational fluid dynamics (CFD) analysis was used to predict the flow of smoke from a 7MW train fire at various worst case positions along the length of the platform, demonstrating that the smoke level on the escape routes along and off the platforms would be kept above head height, and that smoke movement up towards the mezzanine concourse would be inhibited.

Fire precautions

The station is classified in accordance with the Fire Precautions (Sub-Surface Railway Stations) Regulations 1989 (Section 12 Regulations). All materials, equipment, and components used to fit out the station public areas are non-combustible with Class 0 surface spread of flame, as are all suspended ceilings throughout the station. Automatic fire suppression is fitted in non-public areas -sprinklers in staff accommodation and stores, and inert gaseous extinguishing systems in electrical and communications plantrooms.

An exception to this is the EDF (*Electricité de France*) Energy substation where four-hour compartmentation is provided, as required by EDFE. Risk assessments showed that sprinklers could be omitted from the enclosed machinery spaces of the compact escalators used throughout the station, and suppression omitted from some secondary spaces containing electrical switchgear where no other significant fire risk is present. These assessments enabled Network Rail to seek and obtain the necessary exemption certificates from LFEPA.

11. Glazed overbridge structure.

12. Glazed wall panelling, stainless steel clad bases to the concrete columns and terrazzo flooring feature throughout the public areas, including the platforms.

The Thameslink concourse is separated from the main St Pancras domestic concourse by one-hour fire shutters, operated remotely from the main station control room (SCR), as the main station does not require Section 12 classification.

Automatic fire detection and alarm systems incorporate a voice alarm system in public areas. The detection system is an analogue addressable type, and the fire command centre is in the main St Pancras SCR where the stations share a common Rendezvous Point for the emergency services. The voice alarm is principally used to announce and control a phased evacuation via a staged alarm or “double knock” system, but can also be used for public address announcements by station staff through a link installed to the Thameslink station operation room at platform level.

Finishes

The public area finishes to the Thameslink station mostly reflect those of the main St Pancras concourse areas. Top-lit, demountable, stainless steel-cassetted, obscure-glazed wall panelling is used throughout the circulation areas from ground level down to platform, as is terrazzo floor tiling containing carborundum to aid slip resistance. Stainless steel cladding at their bases highlights the exposed fairfaced concrete columns, giving the necessary contrast for visually impaired passengers.

Stainless steel balustrades and toughened glass-clad escalators and lifts, together with the glass wall cladding, provide elements of sparkle while being robust and practical. High-quality precast concrete wall panels mounted on steel frameworks give attractive, durable boundaries to the platforms, form secure drained cavities to the box piled walls, and provide horizontal routes for piped and electrical services. These cavities also supply vertical routes for the smoke extract ducts dropping from high level above the tracks and platforms into the under-platform smoke extract plenum on the eastern side. The platform surface is terrazzo tiling with precast concrete copers and tactile strip, conforming to Network Rail standards.
Hinged panels at intervals within the coper edge give access to a signalling and communications duct running the length of the platforms. Platform ceilings have polished plaster edge strips incorporating lighting, which frame demountable, linear steel grilles giving access for above-ceiling services maintenance and inspection of the ceiling supports and structure above. Acoustic baffles suspended at regular intervals above the ceiling grilles provide the absorption needed for audibility of platform announcements. Other public ceilings are formed of flat polished plaster incorporating a regular pattern of surface modelling to improve the acoustic performance of the space.

Building services

The principles of servicing the Thameslink station were determined by the client requirement to use as far as possible the central energy, water, fireand communications systems of the main St Pancras station. The box structure also includes the water and fire storage plantroom for the main station, and at its southern end is immediately adjacent to the station energy centre. This planned arrangement enables direct connections into the Thameslink station for heating and chilled water systems, cold water services and a boosted fire supply to serve sprinklers. The energy centre structure also incorporates a large ventilation shaft for the Thameslink station smoke extract discharge.

Public areas are naturally ventilated, with no heating, mechanical ventilation, or cooling. CFD analysis was used to predict temperature rise from train braking and passenger movements, which at certain times of the year, with the full service operating, will exceed the target 5˚C increase above ambient set by HMRI RSPG. This non-compliance was accepted by the client and operator, given the constraints imposed by the orientation of the Thameslink station beneath the new St Pancras International extension and Midland Road, which severely limit the opportunities for creating draught relief ventilation. Station staff accommodation has fresh air ventilation with chilled water fan-coil units providing cooling, and local electric space heating.

Foul and waste effluent is collected by gravity drainage, discharging into a package foul pump at sub-platform level. Perimeter cavity wall drainage, and the below-base slab groundwater drainage system, connect into the pumped discharge system via submersible sump pumps. The discharges are pumped up to ground level from where they flow into the adjacent combined sewer in Midland Road.

A system of dry falling mains was installed for firefighting in the platform areas, fed from a breeching inlet on Midland Road. There is also provision for a future separate wet charged falling main to serve the Thameslink cross-site tunnels when these come into use.

Dual independent incoming station electrical supplies are taken from the EDFE 11kV network installed in the main station, using two of the three surface substations. A dedicated EDFE substation at Thameslink platform level contains all necessary transforming, tripping, and battery equipment. Each incoming supply is rated at 100% of the Thameslink station load to permit switching between supplies under single circuit/transformer failure, and meets the *BS5588* requirements for secondary supplies without the need for standby generation. Traction and signalling supplies are provided independently by Network Rail and are fed remotely from the station. Uninterruptible power supply (UPS) units are provided for life safety and operational systems, such as security and communications equipment racks and station operations room systems.

Lighting

Lighting in public areas and escape routes is interleaved so that at least 50% in any one area will continue to function should the supply fail. Public area luminaires are typically the compact linear fluorescent type, and can be switched in zones from the SCR via the BMS to save energy. Emergency lighting throughout is designated as a maintained system, category M3, with self-contained luminaires in non-public areas.

Public area lighting is fed from two static inverter central battery systems, each sized at 50% of the emergency lighting load. Lighting on platforms is ceiling-mounted above the coper edge, and at high level above the wall cladding. The overhead line equipment (OLE) had to be isolated to maintain the platform edge lighting, due to reduced clearances under the overbridge structures. A proposal to introduce a permanent edge screen suspended from the box roof as protection from the OLE was not adopted.

Security

The comprehensive range of security installations includes CCTV with full identification capability at main concourse and escalator/stairway entry and exit areas, and recognition at other crowd control and passenger information points. Electronic access control systems are fitted on all doors between public and staff areas. Intruder detection is provided at all external doors, including escape exits, and in ticket office secure rooms. Personnel distress alarms are fitted at all ticket windows.

Communications systems include a station data network, backbone fibre and copper cabling, local area networks, telephone systems, radiating infrastructure and station radio system, passenger information system, and passenger information points. All systems are designed to integrate with the main St Pancras International communications systems and are controlled from the St Pancras SCR directly above the Thameslink station.

Conclusion

The new St Pancras International Thameslink station was opened on 9 December 2007, allowing the existing King's Cross Thameslink station, which had narrow platforms and could not be easily extended to take the planned 12-car trains, to be closed.

Since the opening of the new station, the Thameslink scheme has developed further and work has started to radically increase the capacity of the core section between St Pancras and London Bridge. In addition, the opening of the King's Cross Northern Ticket hall in 2010 will provide an efficient and quick connection between the new St Pancras International Thameslink station and the London Underground network, thereby creating a major transport hub at King's Cross St Pancras.

The Thameslink box will also enable a rail connection for the Thameslink network to be made to the East Coast main line in the future.

Adam Chodorowski is an Associate Director of Arup with the Infrastructure Group in London. He is a civil/geotechnical engineer and had several roles on HS1 Contract 105, St Pancras, including RLE design manager for the Thameslink Box.

Martin Gates-Sumner was formerly an Associate Director and is now a consultant to Arup. As part of RLE, he had various senior roles on HS1 including Area 100 Project Engineer. He was the Project Leader for the new St Pancras International Thameslink station.

Credits

Client: Union Railways **Designer and project manager:** Rail Link Engineering (Arup, Bechtel, Halcrow, Systra); key Arup staff – Jomar Baquiran, Colin Bennie, David Bosher, Gill Brazier, Bob Cather, Adam Chodorowski, Jill Donnelly, Len Griffin, Kelvin Hindson, Tim Hocombe, Martin Hooton, Laura Kidd, Susan Lamont, Conor Lavery, David Lewin, Michele Mangione, Kate McDougall, Kelvin Moneypenny, Chris Murgatroyd, Andy Ross, Stephanos Samaras, Neil Shepherd, Joe Sumners, Graham Tivey, Mike Winterson, Eddie Woods
Joint venture contractor CORBER (Costain O'Rourke Bachy Emcor Rail) **Illustrations:** 1-5, 11-12 RLE; 6-9 CORBER; 10 Nigel Whale.

References

(1) Channel Tunnel Rail Link Special Issue. *The Arup Journal*, *39*(1), 1/2004.

(2) http://en.wikipedia.org/wiki/Observational_method_%28geotechnics%29#cite_note-0

(3) BRITISH STANDARDS INSTITUTION. *BS5588: Part 6: 1991*. Fire precautions in the design, construction and use of buildings. Part 6: Code of practice for places of assembly. BSI, 1991.

1. Viewed from the Museum's Wildlife Garden, the completed Darwin Centre Phase Two complements the Victorian architecture of the original Waterhouse Building.

Darwin Centre Phase Two, Natural History Museum, London

Matt Clark Ed Newman-Sanders

> **"The realisation of the Darwin Centre represents one of the most important developments undertaken by the Natural History Museum, since it moved to its present site in 1881."**
>
> Sir Neil Chalmers, Emeritus Director, The Natural History Museum

Delivering the vision

The Natural History Museum (NHM), designed by the eminent Victorian architect Alfred Waterhouse and now listed Grade I, opened on Exhibition Road, London, in 1881. Drawing originally on collections from the British Museum, its holdings now cover some 70M items within five main collections: Botany, Entomology, Mineralogy, Palaeontology, and Zoology.

The new Darwin Centre houses the preserved specimens; Phase One exhibits the Museum's 22M specimens stored in alcohol, while Phase Two houses the 17M entomology and 3M botany specimens. Phase One has been fully operational since September 2002, and welcomed more than 320 000 enthusiastic visitors in its first year. Phase Two, the subject of this article, was opened in September 2009 by HRH Prince William, who said: *"As the superb facilities of the new Darwin Centre show, the Natural History Museum is at the very forefront of research. This magificent new wing will further enhance the museum's peerless reputation."*

The NHM developed a unique concept for a new type of public access to the Museum's vast collections and the scientific research. In the words of Sir Neil Chalmers, NHM Emeritus Director: *"The challenge for the architect and design team is to introduce public access to a working scientific establishment in an exciting and innovative way... whilst allowing the day-to-day workload of the scientist to continue without interruption... Our goal is to enthuse, empower and educate, to enable more people than ever before to gain a genuine understanding of science and the world about them."*

The Danish practice CF Møller Architects was appointed in November 2001 to deliver this vision with the support of Arup providing structural engineering services. CF Møller distilled the Museum's vision into three fundamental drivers:

Preservation

The primary function of the building is to protect, conserve, and sustain the existing dry entomology and botany collections in pest-resistant areas with stable environmental conditions, where risk from fire or any other damage is reduced to an absolute minimum.

Public access

In addition, the aim was to steer away from the traditional concept of the museum as an exhibition of historical artefacts, and to increase public awareness of the collections and their importance to research, through the architecture and interaction with the scientists and the collections.

Research

To enable world-class research facilities, it was essential to ensure the flexibility, functionality, environmental and architectural standards required for the laboratory and curatorial areas, with easy access to the collections.

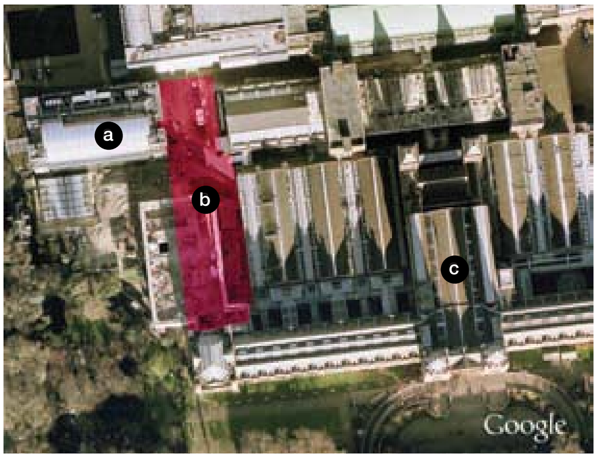
Structural overview

The NHM is one of England's cultural gems; its buff and blue terracotta colours create a unique architectural expression in London. Whereas Phase One of the Darwin Centre was constructed as a separate building beyond the north-west corner of Waterhouse's masterpiece, Phase Two now forms a culmination to the original 1868 scheme, extending south-north to complete the west wing in a contemporary architectural language and linking the Victorian building with Phase One.

CF Møller's response to the design challenge was to create a minimal nine-storey glass vitrine enveloping and displaying a vast cocoon within. It is the cocoon that both symbolically and literally provides the environmental protection to the collections. The main engineering challenge Arup faced was to deliver an efficient and affordable structural solution to the complex geometry of the 65m long, 12m wide, and eight-storey high cocoon.

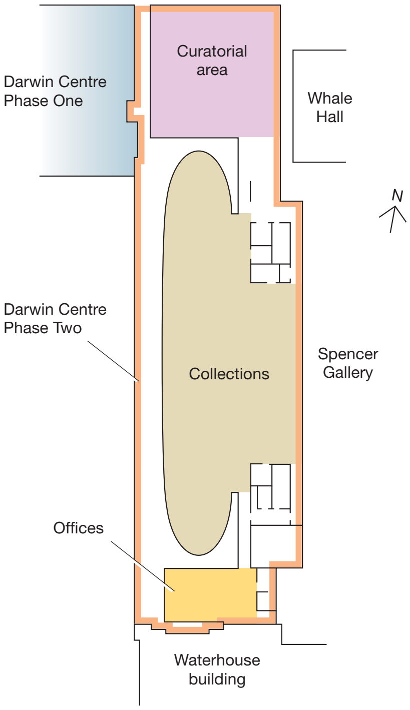
The "dry" collections are stored on mobile shelving which is assumed to impart a load of 12.5kPa to the supporting structure, equating to a 1.25m depth of water. The surrounding superstructure, C-shaped on plan, comprises reinforced concrete flat slabs supported on reinforced concrete columns and walls. The basement slab and retaining walls are also of reinforced concrete construction and founded on pile-caps and ground beams supported by bored concrete piles. A single-storey basement accommodates the mechanical equipment required to maintain the environment of the cocoon. Beyond the cocoon, there is a north wing for research activities, with an additional ninth storey housing the staff common-room (Fig 4).

The primary atrium structure supporting the glazed façade and the triple-layer translucent ETFE (ethylene tetrafluoroethylene) roof pillows is of fully welded fabricated steel members. The atrium frames are free-standing and only restrained at the top along the western and eastern edges by a "structural gutter" and a fabricated beam, connected to the reinforced concrete structure (Fig 6).



2. Aerial view of the Natural History Museum showing:
(a) Darwin Centre Phase One; (b) Darwin Centre Phase Two;
(c) Waterhouse Building.

3. Long section through Darwin Centre Phase Two.



4. Typical floor plan.

5. Internal view of the completed cocoon.

7. Cocoon end showing polished plaster finish with expansion joints.

6. Atrium steelwork.

The cocoon structure is formed from a continuous sprayed reinforced concrete shell, typically 250mm thick, supporting internal flat slabs. This solution maximises the internal net area by avoiding the need for perimeter columns, provides thermal mass to maintain temperatures within the cocoon, ensures flexibility of services distribution, and avoids inaccessible areas for cleaning.

The building is stabilised laterally by a series of vertical cantilevering reinforced concrete cores and shear walls. Lateral loads are transferred to these stability elements by the floor slabs acting as stiff diaphragms. The cocoon shell gains lateral stability by being tied into the concrete floor slabs, which are in turn stabilised by the cores.

The cocoon

Concept

A cocoon is the normal place for a pupa to grow before emerging as an adult insect. The architect extended this analogy to the cocoon being a good place to protect its body from harm once dead. The main cause of this harm in the previous buildings was the Museum's living pests, dining on the botany and entomology specimens, and then reproducing their next generations.

The cocoon is the iconic centrepiece of the building and its structural sprayed concrete shell, on an unprecedented scale, forms the perfect response to the questions posed by the architectural form and the environmental requirements. Expansion joints in the polished plaster finish extend this analogy, appearing as silk threads crisscrossing the surface (Fig 7).

The need to form the curved geometry without incurring high construction costs presented one of the most complex design challenges. The cocoon's varying curvature and non-developable shape precluded a conventional approach to efficient modularisation of structural components or formwork, prompting Arup to look at more homogeneous and innovative construction methods. Options such as steel mullions supporting cladding panels, precast concrete, and in situ concrete formed from CNC (computer numerical control) cut polystyrene moulds, were investigated but eventually rejected in favour of sprayed concrete.

The sprayed concrete could not only be formed to the required geometry, yielding a uniform thickness of insulation and polished plaster finishes, but also sprayed to a thickness whereby it could hold its own shape and resist vertical loads, thereby eliminating the need for a conventional supporting sub-frame. In this way this elegant engineering solution became by far the most expedient, as the extended programme implications of bending individual steel mullions or producing uniquely curved shuttering would have led to significant delays.

Another important factor for this choice of structural solution was the Integrated Pest Management (IPM) requirements, which ensure that living pests do not destroy the dead insects and plants in the collection. This is achieved by controlling the temperature of the environment with the thermal mass of the internal exposed concrete surfaces, and ensuring that all surfaces can be easily cleaned by avoiding nooks and crannies where pests can hide.

The idea of using sprayed concrete technology to form the structural skin of a building was conceived by Arup and had been used at this scale only once before – to support the façade substrate of the iconic Selfridges Building[1] in Birmingham, England. The cocoon is the next generation and an evolution of this technology in that the shell forms part of the primary vertical load-bearing structure from which all movement joints have been eliminated. This was very much anticipated at that time and it was recognised that this technology would "undoubtedly lead to other buildings 'borrowing' the techniques and solutions", as the desire for amorphous forms increasingly becomes an architectural norm.

Geometry

The architect's design philosophy was captured as follows: *"It's a question of magic, you don't want to show the cocoon all at once."* It conveys the message of its purpose, namely that though the cocoon holds 20M specimens (Fig 8), 90% of the world's species remain to be discovered or classified – ie nature is so enormous it can never be seen all at once. Similarly, the cocoon cannot be viewed in its entirety from any one vantage-point.

The key to successful design from the structural engineering perspective was the architect/engineer collaboration, resulting in a shape that both satisfied the ambition for the project and by observation would work as a structural shell. Once a suitable shape was derived, the shell could be set out as a thin-walled section and holes could be considered early in the design process with confidence that the structural integrity would not be compromised. Also with such a shape, initial analysis could be simple and intuitive and not rely on the use of sophisticated finite element (FE) software early in the design.

Using *Rhinoceros* (*Rhino*) software, the Arup team fine-tuned the amorphous surface geometry and created the model of the cocoon structure, including all internal and abutting structures, from which the structure was directly built by the contractor. Without knowing his preferred construction method, it would have been impossible to know where to cut and dimension the vertical and horizontal sections through the cocoon for the construction information (Fig 9).

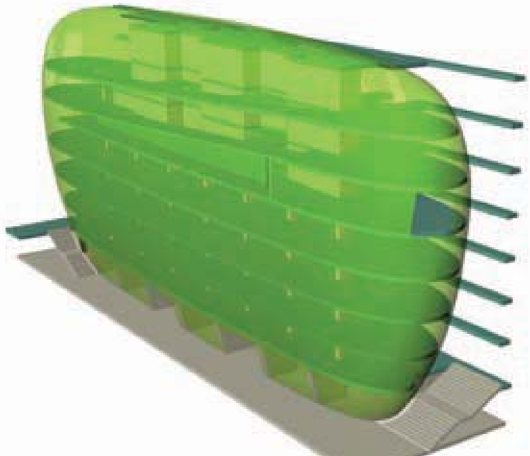
8. The Darwin Centre Phase Two houses 20M specimens.

Analysis and design

The cocoon shell was designed using a range of analysis techniques, engineering intuition, and rationalisation. Since building the doubly curved shell was a significant challenge in itself, the aim of the design was to create a generic cross-section with constant thickness, and a reinforcing strategy that would be applicable for most of the shell. The benefits of design simplicity for the construction process were seen to outweigh materials savings if a minimum material quantity strategy was adopted. In fact, the final shape chosen distributes the forces evenly around the shell, so that there wasn't a large penalty in terms of quantity by selecting constant wall thickness and reinforcement layout.

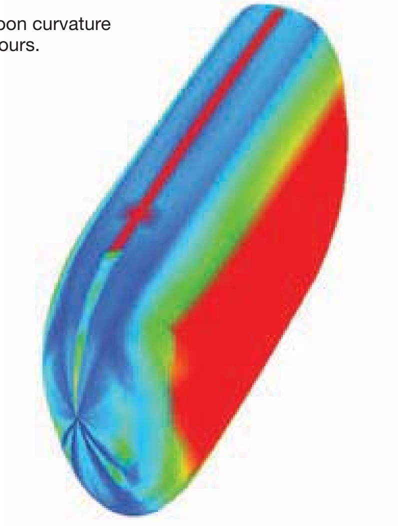
Design of the central portion

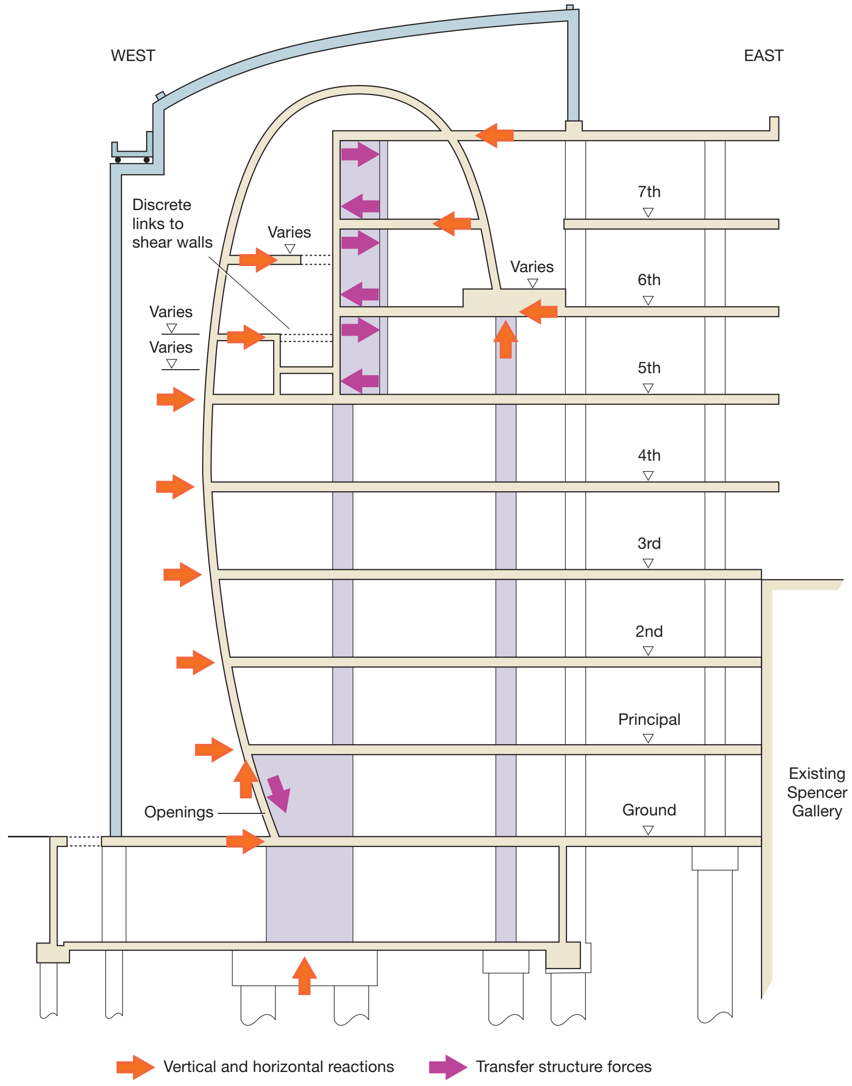
The cocoon is doubly curved at all positions on its surface, but the elongation of the shell along the north-south axis allowed the central portion of the structure to be considered as a plane frame problem for initial analysis, with the primary curvature being vertical (Fig 10).



9. Cocoon structure modelled using *Rhino*.

10. Cocoon curvature contours.





11. Forces in the cocoon.

The shell's cross-section in this central portion is a simple arch some 8m tall above the sixth floor (Fig 11). The east side of the arch sits on columns at the sixth floor and the resulting arch thrust is imposed on the sixth floor slab. The opposite west side does not tie directly to the same floor slab, but instead is restrained by a series of internal ramps spanning horizontally, and by the fifth floor slab. The ramps and slabs transfer the in-plane forces back to various internal structures. Since the arch tie forces are imposed on slabs at different levels, shear walls are required to resolve the arch tie forces.

The west side of the arch continues down to principal floor level, where the shell wall transfers load to perpendicular walls that continue through the basement to the foundations. The interface between shell and columns is through a floor-deep shear transfer rather than direct bearing, so as to maintain the shell's thin wall section. This also allowed large openings at ground floor level on one side of these transfer walls for exhibition spaces. The design of these openings was by strut-and-tie hand calculations, informed and checked by the FE analysis and design.

The cocoon arch above the sixth floor is so shaped that little bending is created in the section; the largest bending moments are created by the ramps and slabs that are attached to the wall, even cantilevered directly off the wall in places. The cocoon wall is vertically curved at all positions between floor slabs, which creates bending in it, but the wall's greatest bending moments are caused by the fixity of the 350mm thick floor slabs that it supports. The axial load in the wall helps the design of these connections.

Considering the system as a plane frame, the bending moments were readily predictable in simple analysis models and hand calculations. Reinforcement was provided according to these moments and their interaction with axial force, and this design was subsequently checked in the 3-D *Sofistik* analysis model. The resulting design was a simple ”background” reinforcement arrangement with additional bars placed where required to meet the increased bending requirements.

Design of the cocoon ends

The double curvature at the ends of the cocoon made the analysis more complicated and bending moments more difficult to predict by simple methods. However, by observation the shape helps to stiffen the wall and reduce moments. In these areas, the Arup team used the 3-D model to assess the wall's performance, with the final reinforcement selection by hand.

The most highly stressed areas of the cocoon are the end walls at the base of the shell, where the surface is most inclined and where curvature is greatest in both directions. Here the higher horizontal curvature of the wall sets up horizontal “hoop” stresses that help restrain the wall from expanding outward due to vertical curvature. Thicker wall sections and more reinforcement were used in these areas to match the required capacity.

Plots of the axial forces and moments, for both magnitude and direction, were used to rationalise the doubly-curved wall areas into groups that could then be designed to specific capacities, informing a simple general reinforcement layout. Alongside this method, the reinforcement design module in the 3-D analysis software was run to provide a second check of the solution.

The concrete's non-linear behaviour was modelled and used to provide a second estimate of the extent of cracking in the shell – which was found by observation to be small, as much of the shell is in compression with little bending.

12. Visitor space in the cocoon.

13. Scientists in the molecular laboratory looking over the cocoon.

Analysis model

The shape of the structure required a full 3-D FE model to be able to accurately predict forces and to check hand calculations for shell forces and moments, slab diaphragm forces, and shrinkage calculations. The long-term creep effects of the sloping surface, together with the potential differential axial shortening between the stiff shell and the adjacent columns, also had to be modelled.

The shape of the cocoon was derived from and existed as a collection of NURBS* surfaces in the *Rhino* model. The adjoining structure was then modelled as centreline surfaces of slabs and walls and centrelines of columns within *Rhino*. The designers carefully aligned centrelines at connections; this meant often departing slightly from the true geometry so as to create a simple FE mesh, avoiding areas with unnecessarily high concentrations of small elements. Less detail was required in the structure away from the cocoon, so the geometry was simpler in these areas.

Each core wall was modelled as a single vertical 1-D element and given a suitable stiffness as calculated in a separate analysis. This greatly simplified the 3-D model and allowed shear and bending forces in the core walls to be simply extracted.

The cocoon centreline surface was split into a collection of quadrilateral elements, meeting the slab and column centrelines. The geometry was imported from *Rhino* into *AutoCad* and the surfaces were redefined and meshed to the desired density with *Sofistik*'s meshing module as a plug-in to *AutoCad* (Fig 14).

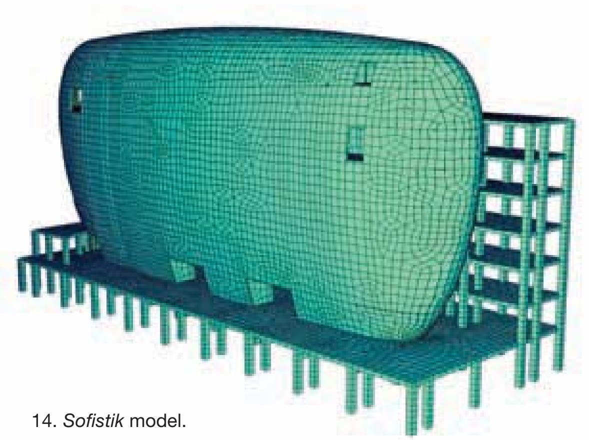
The text-based interface of the FE program was used extensively to manage the model, allowing the designer to specify loading, analysis routines, combination cases, design and reinforcement parameters, results extraction, and graphical representation from within spreadsheets linked to the text file, rather than from within a graphical interface that was slow and difficult to navigate due it its size. Multiple analysis and design runs could be carried out overnight without opening the large model, and the desired graphical results in the form of organised contour plots would be automatically generated.

Reinforcement design

Rationalising the reinforcement bars was key to the simplicity and success of the design and construction. The reinforcing mat layout was resolved early in the process, before the exact quantities of reinforcement were known. The double curvature required reinforcing bars to be laid out carefully so that multiple overlapping layers were avoided where the orientation of the bars on the surface change, with rectilinear arrangements of vertical and horizontal bars chosen for the most constant central portion of the shell.

Radial arrangements were selected for the north and south ends. Here the horizontal bars follow lines of latitude with constant spacing, while vertical bars follow lines of longitude with additional bars introduced to maintain the minimum spacing required. Smaller bars at closer centres were favoured so as to be easily curved on site and minimise difficulties at laps (Figs 15, 16).

The shell was broken into similar areas, chosen by observation of the preliminary results from the 3-D models. The areas were derived by being grouped into similar levels of force, and shaped according to where changes in the reinforcement could be accommodated with the least degree of fixing difficulty. These groups were set up in the 3-D FE model and maintained through the design process as a simple reference system.



14. *Sofistik* model.

15. Cocoon reinforcement.

16. Completed concrete surface.

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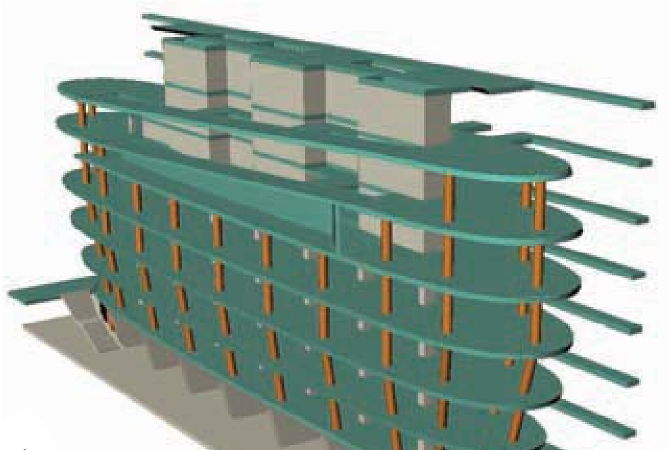
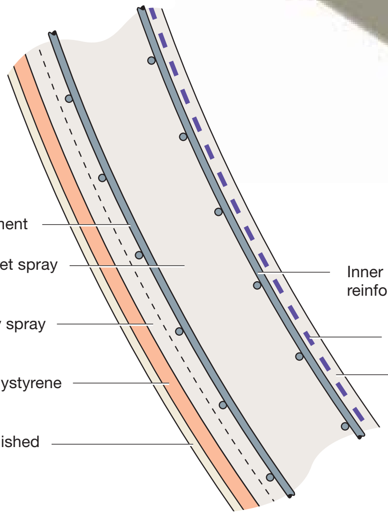
* NURBS (Non-Uniform Rational B-Splines) are mathematical representations of 3-D geometry that can accurately describe any shape from a simple 2-D line, circle, arc, or curve to the most complex 3-D organic free-form surface or solid. Because of their flexibility and accuracy, NURBS models can be used in any process from illustration and animation to manufacturing[2].



18. Internal cocoon structure and temporary columns.



17. Section through cocoon shell.

19. Cocoon slabs with protruding starter bars.

20. Expanded metal mesh connected to the inner shell reinforcement.

21. Temporary columns with spraying of the concrete shell in progress.

22. Wet spraying the cocoon.

Construction methodology

Concrete shell

Quasi-permanent sloping reinforced concrete columns around the cocoon perimeter, which temporarily supported the slabs in advance of shell construction, were constructed with the main frame and then demolished once the structure was complete and had achieved design strength. This approach initially seemed counter-intuitive, but actually generated significant savings over the more conventional steel temporary works originally proposed (Figs 18, 21).

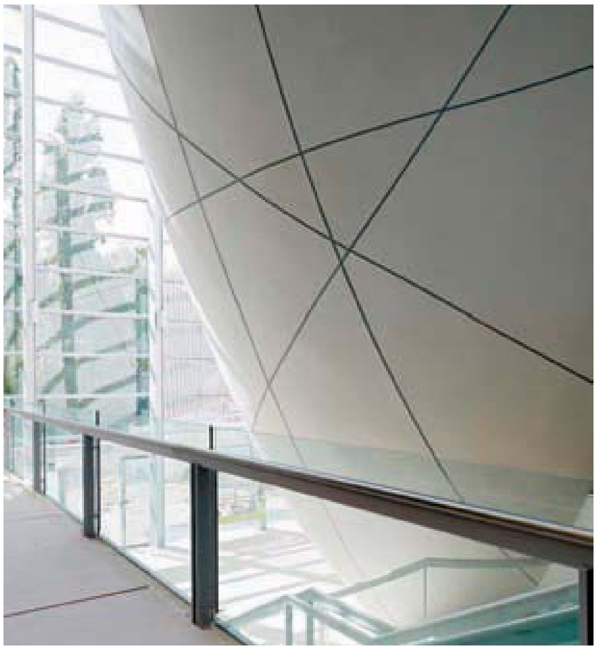
The contractor's initial proposal was to demolish the columns using small jack-hammers, but this was quickly reviewed, after the scientists objected to the noise levels, and replaced by a method which involved sawing the columns into sections and removing them piecemeal. For this solution the floors had to be propped locally in order for the fork-lift truck to track across the slabs.

Due to the mathematically indefinable geometry, presenting the construction information in the form of a 2-D drawing would have been inappropriate and time-consuming. Instead, Arup issued the construction information for the cocoon as a 3-D *Rhino* file. This gave the contractor the opportunity to extract the geometric information that best suited his setting-out and construction methods, which involved a grid of horizontal scaffold poles penetrating the shell and supported by an independent scaffold structure. The inner and outer concrete surface co-ordinates for the grid of the scaffold poles were extracted from the Rhino model and marked on the scaffold tubes on site with sticky tape.

The shape of the cocoon was defined at each floor level by the edges of the slabs, and the reinforcement was then sized so that no pre-bending was required. This enabled the natural curvature of the rebar on site, spanning between the floor slabs, to provide the smooth vertical curvature of the shell. However, prior to placing the shell reinforcement, the slab edge starter bars had to be bent to suit the profile of the cocoon (Fig 19, 20).

23. Finished surface of the wet sprayed concrete above, and the dry sprayed concrete below.

24. Completed cocoon end showing the polished plaster finish.



Expanded metal mesh was used as permanent formwork, attached to the curving vertical reinforcement and held in position by the scaffold support system. The expanded metal mesh was fixed directly to the inside face of the reinforcement, thus avoiding the need for spacer blocks – an evolution from the method Arup developed for the Birmingham Selfridges building, in which the expanded metal mesh was left exposed internally (Fig 21).

The central through thickness concrete was placed by pumping and spraying a wet concrete mix directly onto the expanded metal mesh to a thickness of typically 200mm from the outside of the shell (Fig 22). A 25mm thick dry mix was then used for both the internal and external layers, using a pre-bagged mix with smaller aggregate to allow a final trowelled finish suitable to receive the 50mm thick polystyrene insulation and polished plaster finish. With the dry spraying operation the water is introduced at the nozzle to allow more time to achieve a smooth finish, and without the time and cost pressures of a waiting concrete truck (Fig 23).

Polished plaster finish

The surface patterning of beads to generate the “woven” appearance was generated using a bolt-on program to *Rhino* called *Toycar*. Locking the virtual steering of the *Toycar* and “driving” it across the surface of the cocoon generated setting-out that ensured the beads were only bent in one direction and not warped. This method also ensured that cutting the groves into the polystyrene to receive the beads was as simple as driving the car over the virtual surface.

Other than these geometric constraints imposed on the beads, the only other limitation to their setting-out was to ensure that the maximum area and maximum linear dimension of any one plaster panel bounded by the beads, doubling up as movement joints, was limited to ensure the plaster surface does not crack (Fig 24).

The sprayed concrete shell was delivered in 22 weeks, two weeks under the original programme and significantly less than the timescales associated with the alternative structural solutions. This equated to 130m² each week.

The cost of the 2800m² concrete shell was on budget and again significantly less than the alternative solutions.

Conclusion

The Darwin Centre, and specifically the cocoon, demonstrates the efficient delivery of a highly functional yet geometrically complex structure – Arup bringing innovation to the built environment, and a prime example of successfully synthesising form, function, materiality, construction methodology, and information exchange.

This project demonstrates that close collaboration coupled with innovative design and construction techniques can deliver elegant yet highly functional and environmentally sensitive buildings. The benefit of the Natural History Museum to society is immense in enriching and broadening our understanding of the natural world and raising awareness of the natural world in a very accessible way.

The NHM Project Director, Richard Toy, said: *“Arup has gone beyond the requirements of their appointment to provide innovative and cost effective structural solutions for this important and complex building, allowing the Museum to match its aspirations to the funds available.”*

The project continues to be submitted for awards. It won the award for “Arts or Entertainment Structures” at the Institution of Structural Engineers’ Structural Awards 2009 on 9 October, fittingly held at the Natural History Museum, and most recently was the Overall Winner of the Concrete Society Awards 2009.

Matt Clark is a senior engineer with Arup, now based in the New York office. He was responsible for the analysis and design of the cocoon structure on Phase Two of the Darwin Centre.

Ed Newman-Sanders is an Associate Director of Arup in the Buildings London 5 Group, and was Project Manager and lead structural engineer for Phase Two of the Darwin Centre.

Credits

Client: Natural History Museum (NHM) **Architect:** CF Møller Architects **Structural engineer:** Arup – Roman Buffat, Neil Chadwick, Matt Clark, Joseph Correnza, Ian Feltham, Mariella Gallo, Fred Gamester, John Lange, Bryan Marsh, Ed Newman-Sanders, Hayden Nuttall, Keisuke Tanikawa **Services engineer:** Fulcrum Consulting **Cost consultant:** Turner and Townsend **Project manager:** Manly Development Services **Main contractor:** HBG **Subcontractors:** Westpile (piling), McGee (enabling works), Getjar (concrete frame), Shotcrete (concrete cocoon), Watsons (steelwork), Covertex (ETFE pillows), Permisteelisa (cladding), Armourcoat (polished plaster) **Illustrations:** 1, 5, 7-8, 12-13, 24 NHM; 2 Blue Sky/Google Earth; 3 CF Møller Architects; 4, 11, 17 Nigel Whale; 6, 15-16, 19-23 Ed Newman-Sanders; 9-10, 14, 18 Arup.

References

(1) CLARK, E, *and* GILPIN, D. Selfridges, Birmingham. *The Arup Journal*, *40*(1), pp2-10, 1/2005.

(2) http://www.rhino3d.com/nurbs.htm

1. The Embassy as it is today.

The British Embassy in Rome:

Collaboration between Spence, Nervi and Arup

Prof Brian Edwards

The integration of architectural, structural, and environmental strategies at the British Embassy in Rome (completed 1971), remains of particular interest for its adoption of passive means to moderate the Italian climate, using thermal capacity, solar shading, and natural ventilation before such approaches became common in modern Western building.

Introduction

In 1960 the then UK Ministry of Public Building and Works (MPBW) appointed Sir Basil Spence as architect for its new British Embassy in Rome. Spence in turn advised the Ministry that he would like Arup (or Ove Arup & Partners, as the firm was then named) as structural engineer[1]. The project also initially involved the architect and engineer Pier Luigi Nervi, whose sculptural structural forms were significant for the building's ultimate design. This article seeks to shed light on how the approaches to structural and environmental design were incorporated with other functional and aesthetic priorities to produce one of Spence's more iconic buildings.

When Spence was appointed, buildings in hot climates were already being influenced by new approaches to environmental design. The concept of "tropical architecture" had evolved over a decade earlier[2], and provided a basis whereby modernist practitioners could reconcile their design approach with a greater regard for local climate conditions and building traditions. Major influences on the new aesthetic opportunities afforded by the approach were the climate-responsive designs of Le Corbusier and the Brazilian Lucio Costa with their visible *brises-soleil* (sun-breakers), deeply-set windows, and heavy construction employed to improve thermal mass. Although Reyner Banham argued[3] that architects at the time had scant interest in environmental design, leaving such matters to building services engineers, it is clear that in the Rome Embassy, Spence and Arup's office ensured that solar moderation was fundamental to the structural and architectural design.

Since this was the first UK embassy building where the effects of a demanding climate were deliberately countered by architectural and structural (rather than mechanical) means, it is used here to show how passive solar design was understood at the time and integrated with other considerations. Specifically, three issues are discussed: (1) to what extent did Spence and the Arup team innovate, using what are today called naturally-responsive or "selective" systems of solar control (using the term "selective" as against "exclusive" as employed by Hawkes[4])? (2) what influence did the MPBW have on the design, bearing in mind its disappointment with the earlier Madrid Embassy[4]? (3) what exactly was Nervi's influence, given that Arup was appointed after Spence had consulted Nervi?

The early design approach

Within a month of being appointed in 1960 Spence set out his design approach for the British Embassy. He cited four main considerations[5]:

- to create a building both efficient and symbolic of Great Britain
- to create a courtyard building whose shape would provide rooms that were quiet, cool and well lit

- to maintain the architectural scale of Rome and harmonise in rhythm and materials with the nearby buildings
- to raise the building on pillars so that the parkland site could continue to be enjoyed from the adjacent Via Settembre.

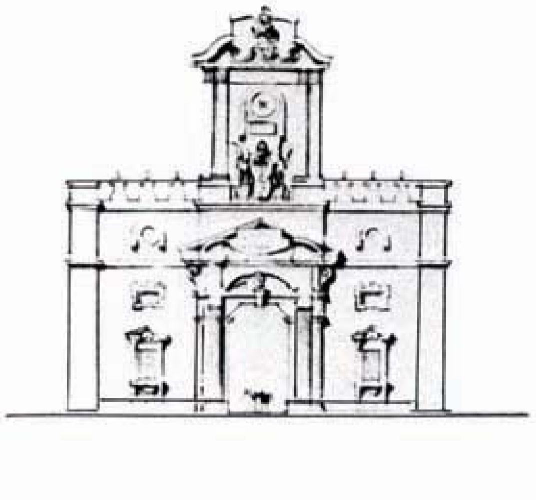
Several points are of interest here. Using the precedent form of a traditional Italian palazzo enabled the "quiet, cool and well-lit" design, and setting it on stilts maximised natural shade whilst permitting deep daylight penetration. For Spence this helped "achieve the combination of practicality and presence which was a feature of the evolving design"[6]. Spence also saw the commission in more weighty terms, referring to the need for the Embassy to respond to Rome's position as the "cradle of our modern civilisation whilst also addressing a demanding climate".

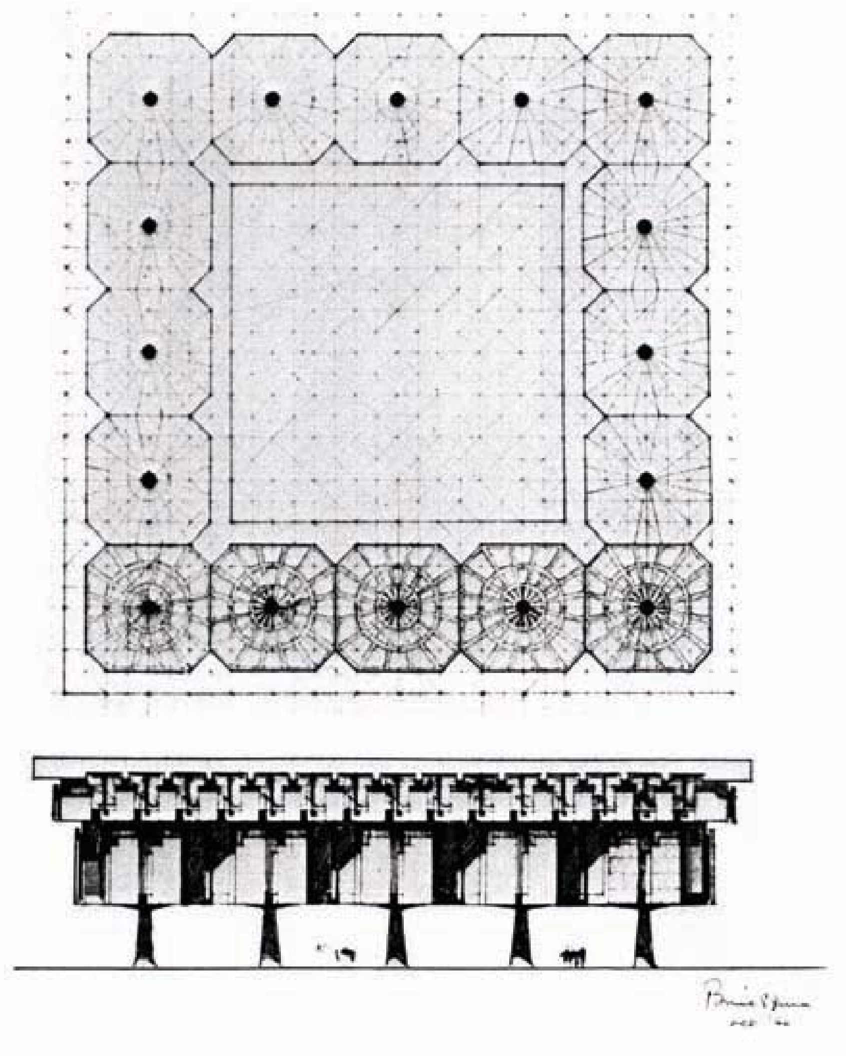
An examination of local Renaissance palaces and examples of contemporary architecture in Italy provided the basis for structural monumentality and environmental design to be simultaneously achieved. Spence also used the word "symbolic", suggesting that he saw the project bringing together cultural, contextual and environmental factors in shaping the perception of British modernism overseas.

A year after Spence won the commission, Arup was appointed as structural engineer (the partner in charge was Povl Ahm supported by Ted Happold as project engineer and Ole Vanggaard as assistant). Spence and Arup's office had earlier collaborated on Coventry Cathedral, which HM the Queen had recently opened. As with Coventry, Ahm was the partner who led operations in Arup's London office.

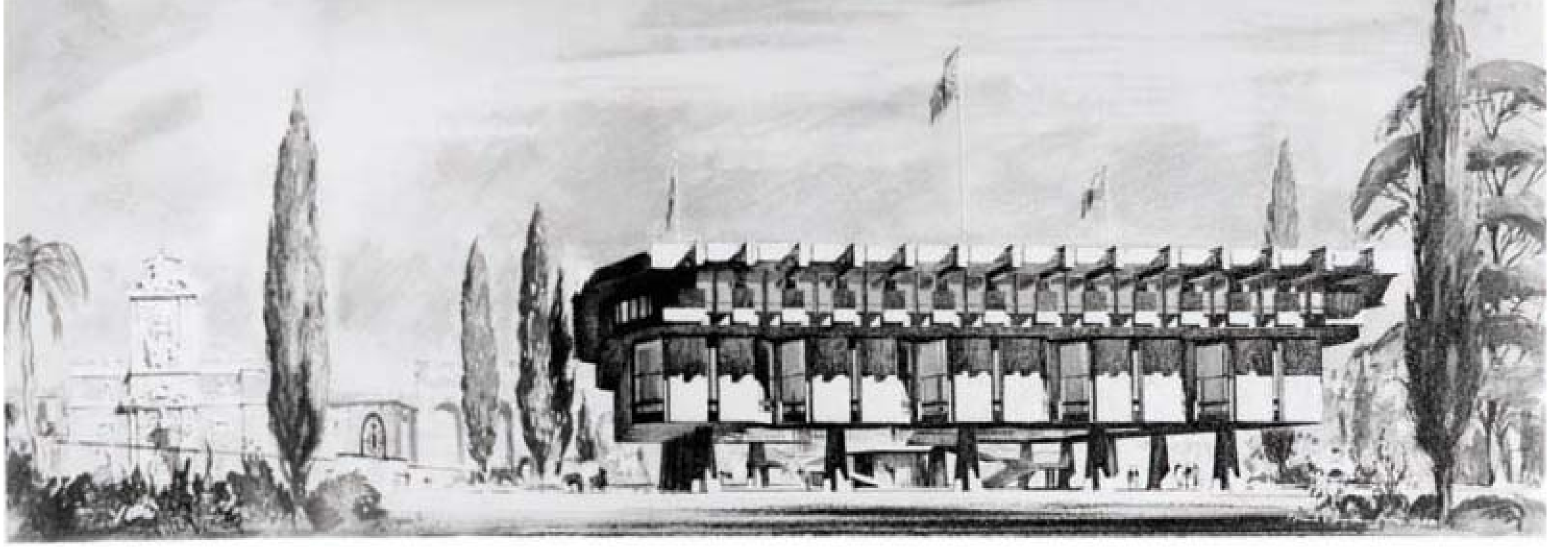
Although the commission proved complex and at times frustrating for Spence (mainly due to UK government indecision, and opposition from the Ambassador Sir Ashley Clarke), he maintained an interest throughout in addressing the need for ventilation and summertime cooling without resorting to full air-conditioning. In this, as he explained, the courtyard shape was an important part of the solution, as was outward stepping of the building section, the use of exposed in situ concrete (for thermal mass), and the adoption of travertine panels throughout for external shading. The latter were held in place with brass fixings 150mm forward of the façade to prevent the sun from directly heating the building.

The Italian palazzo form was admired for its ability to create comfort in a hot climate, and as Michelangelo's Porta Pia was nearby, Spence probably drew direct inspiration from this Renaissance courtyard gateway to Rome. He did a measured drawing of it on his commission and set it alongside one of his perspective sketches as the design matured. As a student in Edinburgh, Spence had attended "History of Architecture" lectures that explored the "origins of architecture, especially the influence of materials, climate and natural position"[7]. In addition, "Principles of Construction" were learnt through historical study, with Renaissance architecture providing a model in the third year of "construction used decoratively"[7]. Such was the integration of historic precedent with modern practices of heating, lighting, acoustics, and ventilation, that in his fifth year Diploma project, Spence was expected to provide evidence, including calculation, "of building science expressed positively in building design"[7]. He would thus have been receptive to any overtures from Arup to use structure to moderate the internal environment as well as support the building and provide it with decorative order.

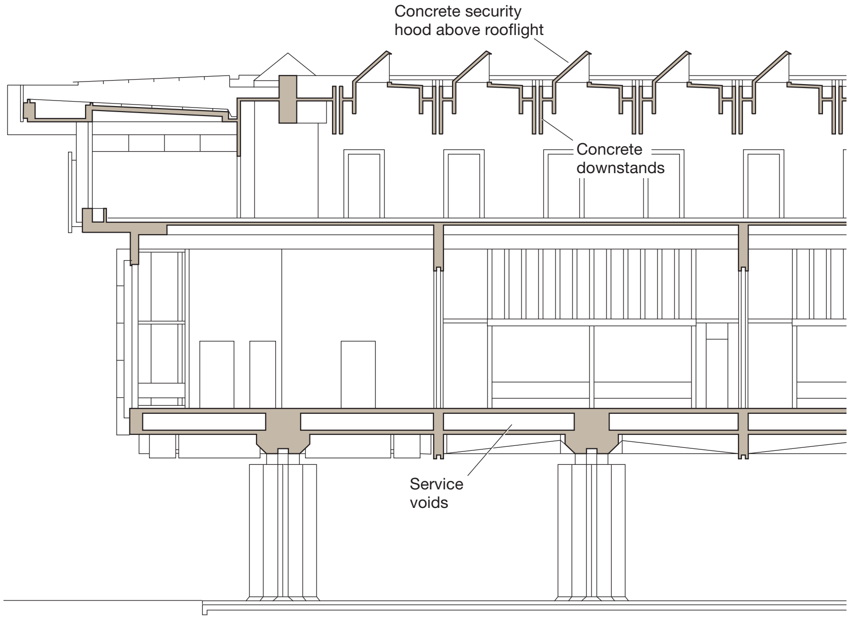




2. Design by Sir Basil Spence of the British Embassy, Rome dated October 1960, showing the design in the context of Michelangelo's Porta Pia. The "string of pearls" structural system – Spence's term – suggests a debt to Nervi's Palace of Labour building in Turin designed a year earlier. Note the triangular columns, again a probable result of Nervi's early involvement. Arup was appointed in April 1961.



3. Perspective drawing by Sir Basil Spence dated July 1962, over a year after Arup's appointment. The triangular columns have survived but the parapet design is much altered.



4. Part section through south façade.

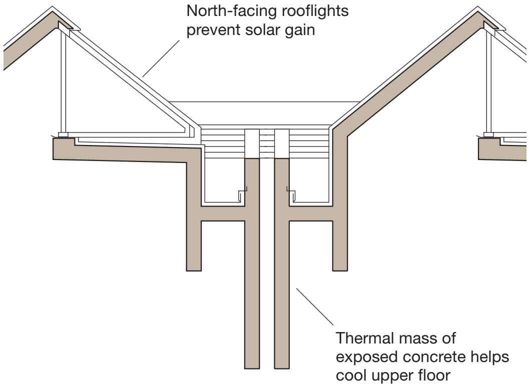
Collaboration between Spence and Arup

Spence's four initial design themes suggest a balancing of modernist and traditional approaches, although behind them was arguably more romantic empiricism than a strong theoretical approach. Arup's appointment in 1961 led to detailed development of the aesthetic, structural and environmental priorities identified by Spence. Not only did the evolving design seek to capture the scale, materiality, and rhythms of construction employed by important neighbours (including the Porta Pia), it adopted the courtyard form, as already noted (Fig 2). As Spence pointed out, the high temperatures and humidity in Rome during summer required particular attention to comfort and cooling, and one benefit of the traditional courtyard layout was that the inner building faces would be protected from the "lower solar altitudes"[8].

Spence and Ahm, against initial opposition from Ambassador Clarke, were convinced that an internal courtyard surrounded by offices overlooking a central pool would provide sufficient shade and cooling air currents to make the Embassy comfortable in the heat of summer without air-conditioning. Although they could not avoid some mechanical cooling, the design team was able to reduce the energy load by creating a large central void cooled in part by the evaporation of water surrounding the courtyard. Comfort and ventilation were particular problems as external windows were not allowed to be opened, the Embassy being under threat of bombing (as had befallen the previous building on the site). As a direct response Spence designed the Embassy so that the courtyard-facing windows could be opened with further light and ventilation provided on the upper floor by lines of north-facing rooflights (Fig 5). The latter, hidden behind angled concrete hoods for security reasons, have exposed concrete downstands whose thermal capacity helps stabilise the temperature of the offices below. The downstands, which provide important structural bracing, were also angled to help deflect daylight into the offices below, thereby reducing the need for electric lighting (Fig 4). The approach was a significant departure from the circular courtyard design of the Madrid Embassy, designed in 1958 by the MPBW's own architect, WS Bryant; this was fully air-conditioned and lacked shading devices and exposed thermal mass[9]. Both embassies shared similar climatic constraints yet adopted very different approaches to environmental design.

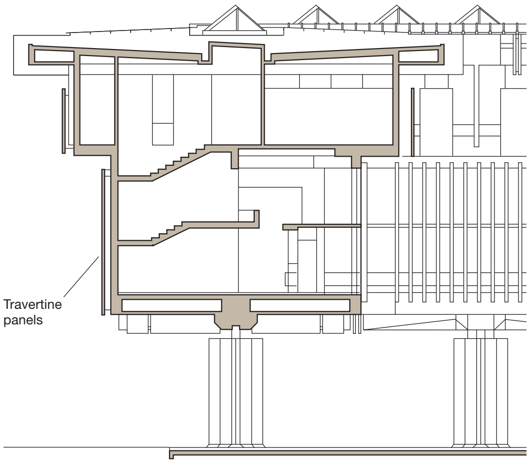
Initially Spence collaborated with Nervi (required under local building law to ensure regulatory compliance) and the MPBW's own services engineer, David Nicholls. Nicholls was familiar with the problem of solar radiation, especially heat gain and glare, having been engineer to the problematic Madrid Embassy. He actively encouraged Spence and Arup to design the Rome Embassy in a more sympathetic environmental fashion. Although Nicholls took a back seat after Arup's appointment he maintained throughout the necessity to avoid expensive and unsightly air-conditioning.

5. Roof detail showing maximisation of daylight without the problems of solar gain (north is to the right).

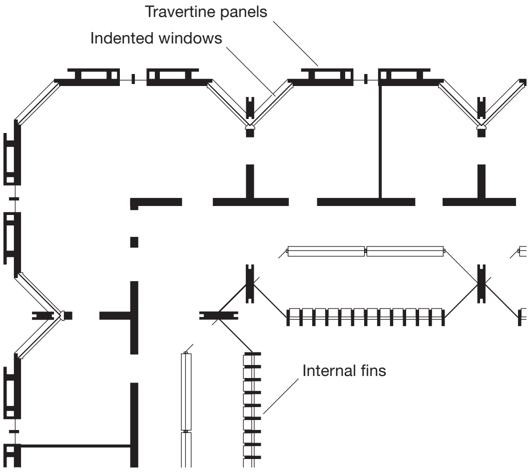


6. Detail of vertical solar shading within courtyard.

7. Section through courtyard façade (right) and south façade (left), showing the independent structural system of each cantilevered bay.



8. Plan showing interacting structural plates.

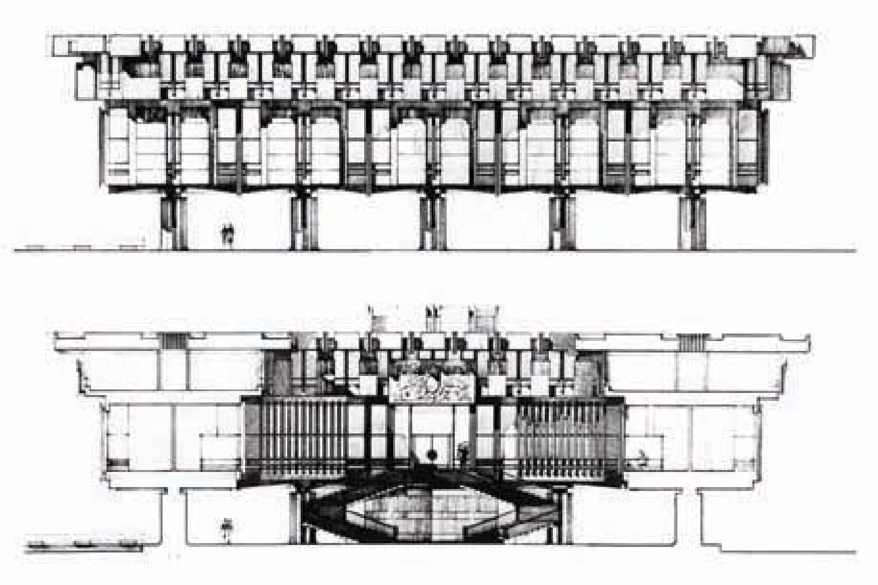


From the lengthy correspondence on this project, it is clear that Spence knew that the courtyard form offered many benefits, architectural and environmental, but to overcome solar gain on the façades he had to develop the outwardly stepped section (Fig 7) and provide shade at the corners. Here, advised by Ahm, he devised diagonal set-backs in plan and placed meeting rooms at the Embassy corners where they would benefit from internal cross-ventilation. As he explained to the Ambassador, the heat and glare of the mid-day sun would be shielded by the overhangs above. Furthermore – and partly to justify the cost – Spence explained how the travertine panels would to be held forward of the building face to prevent solar rays directly striking it. Spence also added that the low late afternoon sun, which by its angle would penetrate deeply into the building, would be screened by fins on the courtyard façades and by the trees in the Embassy grounds (Fig 6). Spence later went to some lengths to move magnolia and cedar trees that would have been lost by the building operations to new positions where they would act as shading.

In the correspondence between Spence, Arup's office and the Ambassador, frequent mention is made of the environmental basis for the architectural and structural decisions[10]. The external travertine panels, stepped section, and indented plan (Fig 7), though elaborate and expensive to build, allowed the building to "look right" in Spence's eyes whilst "providing a significant reduction in solar gain". In the event, the saving on air-conditioning resulted in the Embassy consuming only one-third of the energy of the Madrid building[11]. Also, as the bay widths and storey heights follow closely those employed by Michelangelo at the Porta Pia, the elevations have an essentially Roman scale and rhythm.

To achieve the environmental and visual effects sought by Spence, Arup's office exploited the interaction between structural, aesthetic and climate design. Key to this was the development of a grid of structural spine and crosswalls that sit on ground floor pillars, replacing the internal columns of Spence's early thinking. These exploited plate interaction (as developed in the 1950s at the Technical University in Copenhagen, which Ahm had attended), allowing the concrete walls to provide the necessary structural stability using the ultimate collapse approach* whilst also exposing the interior to the cooling effect of the heavy walls. The new crosswalls divided the interior spaces into compartments suitable for offices, and since each

9. South-west elevation and section through courtyard, June 1964, showing the extent of solar protection on the interior and exterior façades. Drawing by Sir Basil Spence and Partners.



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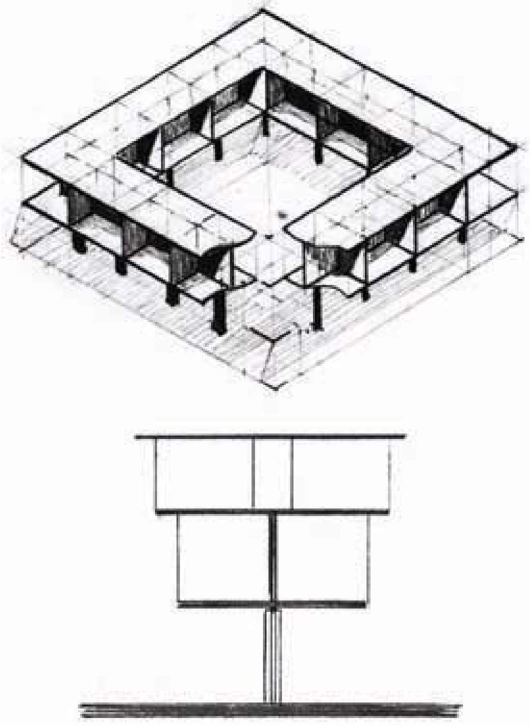
* The technique was developed by KW Johansen at the Danish Technical University and adopted on the British Embassy and other projects in Arup's office in the 1960s.

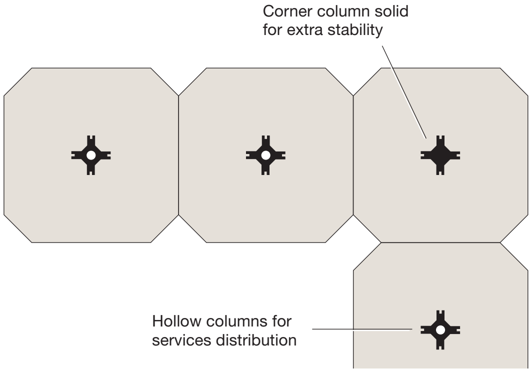
element of construction was a self-contained unit sitting on a pillar, the thermal mass was exposed on many faces. Floor-to-ceiling heights varied also between levels with a lofty piano noble (first floor) allowing the 5m storey height to utilise cross-ventilation and daylight penetration without solar gains. The design had considerable foresight and introduced structural and environmental techniques later employed by Spence (in the Expo 67 British Pavilion) and by Arup's office for projects in Saudi Arabia[12].

The combining of often contradictory requirements into a coherent whole is the key to the success of the Rome Embassy design. No single agenda dominates: the design balances multiple priorities – programmatic, climatic, structural, and civic.



10. Arup sketch (1968) showing the plate system.

11. 1964 plan detail of north-west corner.



12. Façade facing garden with trees preserved by Spence to enhance shading.

Although the stepped section and courtyard form were responses to solar protection, the evolution of the structural elements suggests that Arup's team provided Spence with the technical means to exploit a growing interest in environmental design. They gave the project the means to generate new structural solutions that worked actively in a climatic sense whilst also giving the major façades and interior spaces the necessary visual interest. The intention Spence later reported "was to create a rich interplay of sunlight and shadow... with the elevations constantly varying and complex in response to climate and context"[8].

The Arup team subtly changed the structural design in 1964, and as built it differs from the original sketches. A combination of large cantilevered crossbeams on the underside of the floor slabs, stabilised by loadbearing crosswalls and connected to a spine wall formed an important torsional plate structure to tie together the separate mushroom modules (see below). This provided the rigidity and thermal capacity desired. This innovatory approach released the potential for passive solar cooling, particularly in the context of the courtyard layout (Fig 10). Vanggaard recalls the grey cardboard model that Arup's office took to Spence's to explain the idea.

The design sketches, many in Spence's own hand, show a clear understanding of the integration of structural, spatial, and environmental strategies. The elevations are a direct result of solar control, but inside the building there is a remarkable absence of mechanical services. The general lack of suspended ceilings, the soffits exposed for cooling, and the use of in situ concrete, clay tile flooring and thick panels of travertine, all help stabilise the interior temperature. The Embassy illustrates how 1960s modernism and environmentalism were beginning to be combined to produce buildings that fitted their geographical location ecologically and culturally. With its dual agenda – to serve as ambassadorial offices overseas and project an image of nationhood – embassy architecture inevitably engages in some design propaganda, which perhaps explains why embassy buildings of the period tend to be more innovative than other examples of governmental architecture.

The extensive use of north-facing rooflights helps maximise daylight penetration in the staff offices on the upper floor. The rooflights not only enliven the roofline but are profiled to provide daylight without the discomfort of sunshine. A large-scale pre-tender cross-section of the building drawn in 1964 (Fig 9) confirms that passive environmental systems were developing in parallel with architectural and structural ones. There is extensive use of hollow floors for cross-ventilation, deep narrow floor beams left exposed for night-time cooling, double roof beams which maximise air contact, and concrete spine walls (rather than columns) running through the centre of the Embassy. The justification for such elaborate structural arrangements was primarily climatic but they give the building a scale and materiality lacking in air-conditioned structures.

There was considerable collaboration at this time between Spence's assistant Anthony Blee and Happold, who had earlier worked under Ove Arup's guidance on various school and health buildings in Africa for the architectural practice of Maxwell Fry and Jane Drew. These too had employed *brises-soleil* and heavy concrete in an

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* A complete set of working drawings is held in the Embassy, with early design sketches at the Public Record Office, Kew, London.

attempt to reduce the adverse effects of sunlight. Though Spence was the prime originator of the design of the Embassy, it seems likely that some of the solar shading details (particularly the fins facing the courtyard) found their way to Rome by this channel. Whereas the stepped profile resulted in considerable natural shade to the main façades, it was augmented on the east and west interior elevations by vertical concrete fins held in front of the glazing to overcome the problem of low-angle solar penetration.

Another innovation concerned differential ceiling heights. On the main floor of the Embassy, the ceiling is nearly 5m high whilst above it is only 3m. Where secretarial offices are located on the lofty main floor, these are designed as self-contained rooms with a much lower ceiling height of around 2.5m. This allows air and daylight to pass around and above the offices to the main chancery accommodation beyond. By avoiding storey-height sub-divisions, the interior is kept open, well-ventilated, and cool. The arrangement also allows light from the perimeter to reach interior corridors where artificial light would normally be employed. The attention to working conditions as well as the wider environmental performance of the building marks the Embassy apart from other government architecture of the time.

Vanggaard recalls around 10 Danish engineers working in Arup's office in the mid 1960s, and rough cardboard models of the Embassy being used to test structural arrangements under Ahm's and Happold's critical eyes. Whereas Ahm ensured the design developed soundly from a structural point of view, it was probably Happold who fused structural and environmental forces into the final design as built. In some ways the Embassy was a precursor to the internationalism of practice evident today – designed by an architect born in India (Spence), engineered by Danes and Brits, and given initial structural shape under the influence of the Italian Nervi.

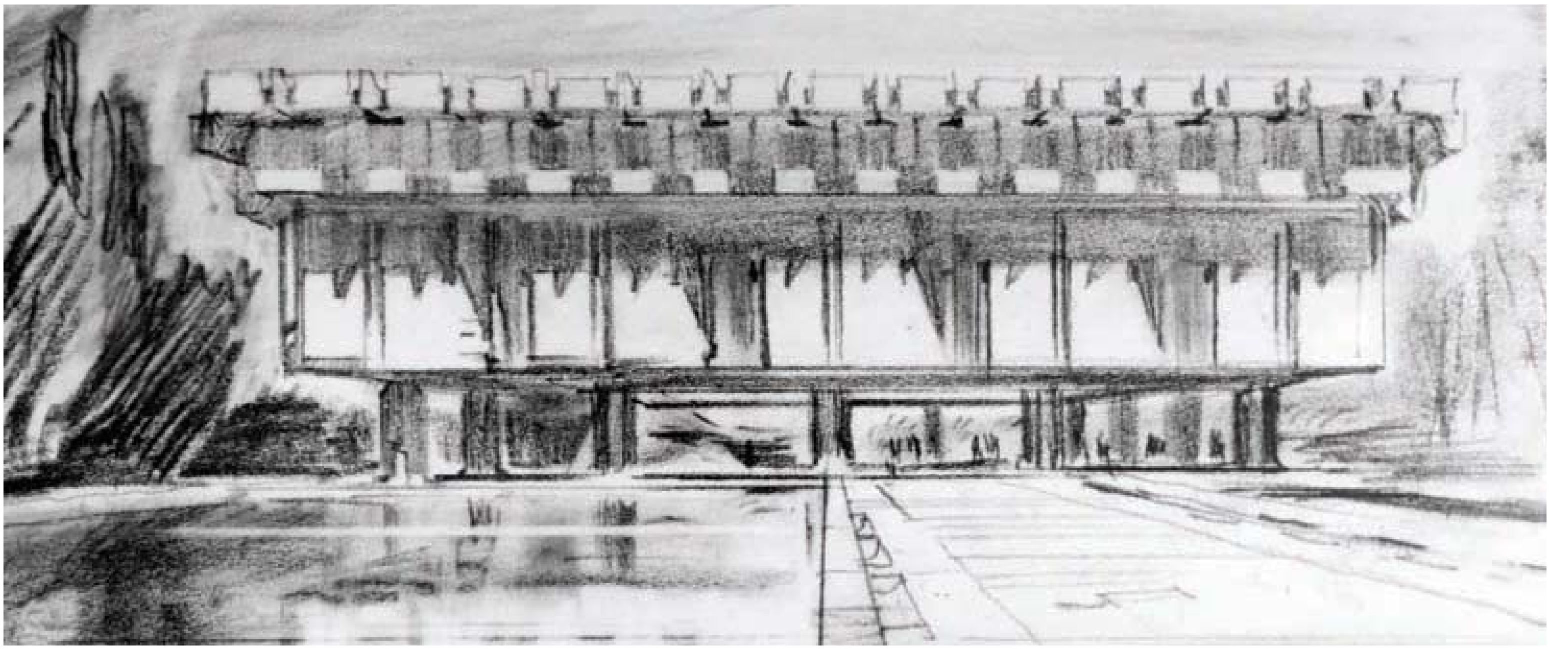
The involvement of Nervi

Spence had met Nervi early in 1960 in his capacity as president of the Royal Institute of British Architects (RIBA) in search of a candidate for the RIBA Gold Medal. He admired Nervi's use of materials (notably concrete and Italian marble) as well as his sports and exhibition buildings, and successfully proposed his nomination for the 1960 Medal[13]. Since for the Embassy project Spence was required under Italian building regulations to establish a partnership with a local architectural or engineering practice, he naturally chose Nervi[14]. By the time the latter was approached, Spence had a clear idea of his design, one priority in which was the need to keep the landscape of the parkland site in view by raising the Embassy on pillars, a decision with consequences for the structural design, as the pillars would now be perceived as part of the wider landscape. Since they were unencumbered by walls, they would assume great visual significance. Nervi appears to have been a crucial influence here, especially as the pillars – 16 independent mushroom-like columns modelled on the Turin Congress Hall (or Palace of Labour as it was originally named) designed by Nervi two years earlier[15] – also follow the splayed arrangement adopted on that project.

As at Turin the columns of the Embassy were joined together to form a necklace, each column and the construction above being structurally independent. The 16 splayed and pointed columns each supports a structural bay which when formed into a square made the armature of the Embassy. Each column was hollowed to take hot water and electricity from an independent boiler-room, except at the corners of the building where Arup subsequently stipulated that they should be solid for stability. By exposing the underside of the structure to cool breezes drawn across the pools of water, the visual effect of a floating Embassy on sculpted columns complements the environmental strategy elsewhere.

Nervi worked with Spence for several months before Arup came on the scene, having been appointed in December 1960; Arup's structural design did not begin until spring 1961. Although Nervi's use of splayed and tapering concrete in situ columns were initially to be replicated in Rome, after Arup's appointment the columns assumed a more orthodox, cruciform shape, with shallow splays at their bases.

13. Pencil perspective sketch by Spence dated July 1968, presented to the Ambassador as a gift to mark the beginning of construction.



Arup's involvement led to other structural changes. Mention has already been made of the torsional plate system sitting above freestanding columns – one of the first such applications of the technique. As the project progressed, other changes were made to ensure the rigidity of the horizontal and vertical framing elements. Using an early 3-D model, tests were conducted under extreme conditions (possible bomb attack) and this led to the introduction of the "hovering" concept of building masses tied together laterally to form a cage. At this point the internal fins, whose original function was climatic, were modified to assume a structural role and the corners of the building were strengthened because of the limitation of plate interaction here.

The design continued evolved under different influences, with ideas from Nervi, Arup, and Spence interacting over the decade-plus that elapsed between commission and completion. What remained, however, was a desire to link into a coherent whole the many structural, environmental, and architectural ambitions, making the building one of the first to integrate them effectively.

Reactions

Financial and contractual difficulties delayed start of construction until 1969. The building was not universally admired when it was reviewed in the architectural press, neither were the aspirations behind the design seen as legitimate in an age of modernist bravado. *Architectural Review* devoted nearly 20 pages to an examination of the design[9], with the architectural critic and academic Bruno Zevi from Italy, the incumbent Ambassador Sir Evelyn Shuckburgh, and Sherban Cantacuzino from the UK reviewing the building from their various perspectives. The three generators acknowledged by Spence and developed with Arup's encouragement – the Renaissance courtyard model, passive climate control, and the Roman context – formed the main basis for the evaluation.

Zevi offered half-hearted praise to the lengths Spence went in order to respond to the context of Michelangelo and Roman palaces generally, and to the specific climatic design features. Though he did not much enjoy the hollow box-like Embassy container and Renaissance tri-dimensionality, Zevi said that the building was "ambiguous enough to be both fascinating and repellent, which is perhaps the highest achievement an architect can hope to attain today". He likened Spence to a mannerist architect, monumental in gesture but not in scale. However, he did acknowledge that the Embassy had something to say about environmental design and structural design, and had added a "factor of quality into the dusty townscape" of that part of Rome. More charitably, Ambassador Shuckburgh described the building as being of the "greatest distinction, ingenious, imaginative, self-contained and worthy of the situation in which it stands". He also noted that it reflects the great architectural traditions of the city and drew attention to the attractive effects of light and shade and Spence's passion for atmosphere. However, he noted the compromises made to the design late in the day in "order to meet the practical needs of the chancery's work".

By contrast Cantacuzino attacked the building's insistent formality, its lack of exterior expression of internal functions, and the mixed metaphors implied by the Porta Pia references. He commended the use of piloti for the way it integrates the building with the landscape, but was critical of the way the stepped section is unmodified by orientation, implying that Spence's environmental claims were merely an excuse for architectural effects. Cantacuzino did, though, concede that the building has "sculptural character".

The reviewers conducted their assessment in the context, at least in part, of the aspirations Spence set himself and that were reflected in the brief. Their views suggest that contextual and climatic interests were acknowledged as legitimate factors to be balanced alongside the demands of function, structure, and construction as early as the 1960s. Thus not only did the building establish an overall architectural order that grew directly from environmental considerations, but in raising them in this important commission, Spence and Arup opened up a fruitful avenue of design innovation. Thus the Rome Embassy can be said to anticipate the current era of sustainable design, in which engineers shape buildings as much as their architects.

Dr Brian Edwards is Emeritus Professor of Architecture (Edinburgh) and Associate Professor of Sustainable Architecture at the School of Architecture, Royal Danish Academy of Fine Arts, Copenhagen. He is the author of several books on sustainable architecture, on transportation buildings, and on Scottish architecture and architects. He has made a particular study of the life and work of Sir Basil Spence, and is author of the entry on Spence in the New Dictionary of National Biography, published by Oxford University Press.

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Credits

Client: Ministry of Public Building and Works **Architect:** Sir Basil Spence and Partners **Structural engineer:** Ove Arup & Partners **Quantity surveyor:** Reynolds & Young **Main contractor:** Impresa Castelli (Rome) **Illustrations:** 1, 6, 12 Su Fahy; 2-3, 9 Sir Basil Spence and Partners/ RCAHMS; 4-5, 7-8, 11 Nigel Whale; 10 Arup; 13 Brian Edwards; 14 RCAHMS.

References

(1) HAPPOLD, E. British Embassy, Rome. *The Arup Journal*, *5*(4), pp11-18, December 1970.

(2) LE ROUX, H. The networks of tropical architecture. *Journal of Architecture*, *8*(3), pp337-354, Autumn 2003.

(3) BANHAM, R. The architecture of the well-tempered environment. University of Chicago Press, 1969.

(4) HAWKES, D. The environmental tradition. E and FN Spon, 1996.

(5) SPENCE, B. Report on Embassy design, 8 December 1960. PRO FO366/3191.

(6) SPENCE, B. Letter to Sir Ashley Clarke, 9 May 1961. PRO FO366/3192.

(7) EDINBURGH COLLEGE OF ART. Prospectus 1934-5.

(8) SPENCE, B. British Embassy in Rome: mechanical and electrical services. Document A. 16 February 1971. Rome Embassy papers. Building File.

(9) *The Architectural Review*, *150*(895), pp149-168, September 1971.

(10) SPENCE, B. Letter to Sir Ashley Clarke, 22 May 1963, with confidential file note. PRO FO366/3264.

(11) Personal communication with Anthony Blee, Spence's partner in charge of project, December 4, 2008.

(12) *The Arup Journal*, *6*(3), pp11-18, September 1971.

(13) PRO. FO366/3264.

(14) HAPPOLD, E. The British Embassy, Rome, *The Structural Engineer*, *48*(11) pp418-419, November 1970.

(15) *The Architectural Review*, *127*(765), pp319-20, November 1960.

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14. The Embassy soon after completion.

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Illustrations: 1. Park Path Bridge at Central Park, Songdo IBD, Korea: KPF and HG Esch; 2. The Thameslink station at St Pancras, London: Adam Chodorowski; 3. Darwin Centre Phase 2, Natural History Museum, London: Natural History Museum; 4. Asia Aluminum flat rolled product facility, Zhaoqing, Guangdong Province, China: Marcel Lam; 5. The Stone Passage, Songdo IBD Central Park: KPF and HG Esch; 6. The British Embassy in Rome: Su Fahey.

Front cover: Tea Mazes in the Mountain Strolling Garden at Central Park, Songdo IBD, Korea. Also visible are Park Path Bridge, one of the Korean Pavilions, and islands in the canal: KPF and HG Esch.

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