

THE ARUP JOURNAL

HONG KONG AIRPORT CORE PROJECTS SPECIAL ISSUE 1/1999



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This edition of *The Arup Journal* is dedicated to **Tom Larmour**, Director of Arup, who was drowned saving the lives of two young men during a typhoon in Hong Kong. Tom's act of bravery was recognised when he was posthumously awarded the Gold Medal for Bravery by the Hong Kong Special Administrative Region. Tom's contribution to Arup's Airport Core Projects, notably the Terminal Building and the LAR stations at Hong Kong, Kowloon, Tsing Yi, and Tung Chung, was fundamental to their success.

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THE HONG KONG AIRPORT CORE PROJECTS



1. Location plan

In 1989 the Hong Kong Government's Port and Airport Development Study (PADS) named the island of Chek Lap Kok off the north coast of Lantau as the site selected for Hong Kong's new Airport.

The project was to be one of the biggest in civil engineering history. Chosen for its clear airspace and convenient proximity to the urban areas of Hong Kong and Kowloon, the originally 302ha island and its smaller 8ha neighbour Lam Chau were to be more than tripled in size through land reclamation into a 1248ha site, now home to one of the world's largest and most sophisticated international airports.

The massive earthmoving and dredging operations involved in creating this vast platform were largely completed by mid-1995, at which time the design and construction of the airport's various components were already well under way.

The new Hong Kong International Airport officially opened on 6 July 1998 and can currently handle 35M passengers and 2.6M tonnes of cargo a year.

Development continues. A second runway is due for completion in mid-1999 and will allow some 50 aircraft movements per hour round the clock, rising to a peak of 80 by 2040 when the Airport will reach its ultimate annual capacity of 87M passengers and 9M tonnes of freight.

Rail transport from Chek Lap Kok to Hong Kong is provided by the Mass Transit Railway Corporation's (MTRC) Lantau and Airport Railway (LAR).

Comprising two separate lines, the Airport Express Line (AEL) links Hong Kong and Kowloon to the airport, while the Tung Chung Line (TCL) is a predominantly domestic service between Hong Kong, Kowloon, and the new town of Tung Chung on Lantau.

Together the airport and rail projects comprise two of the Government's 10 Airport Core Projects.

From its inception the new Airport gave Arup a welcome opportunity to bring its total strength to bear. We seconded a team of civil, marine and geotechnical engineering experts to assist the then Provisional Airport Authority (PAA), later to become the Airport Authority (AA), and provided a wide range of consultancy services.

These contributed significantly to expediting construction and controlling costs.

We went on to fulfil a number of roles for projects at Chek Lap Kok. The firm was appointed as lead consultant for SuperTerminal 1 and the Ground Transportation Centre (GTC), as well as acting as structural designer for the overall superstructure scheme design and for detailed design of the roof and all visible steelwork at the Passenger Terminal, where we were also fire and acoustic engineers.

We also played a key role in the construction of facilities for specific carriers. Arup was the IT and communications engineer for Cathay Pacific's high tech passenger lounge, and project manager for Lufthansa's new catering facility.

Equally significant was our contribution to the LAR. Of its seven stations, we were involved with five, including the Airport station housed in the GTC. Each required a unique combination of our areas of special expertise.

At the line's flagship development, Hong Kong Station, Arup Associates were architects and Ove Arup & Partners engineers. At Kowloon, Tsing Yi and Tung Chung we engineered the station buildings, and associated civil engineering work including viaducts, tunnels, and roads.

Of these, Hong Kong, Kowloon, and Tsing Yi are all megastructures incorporating massive commercial developments.

While acting as consultants in fire and acoustic engineering for the entire LAR, as engineers for the platform screen doors and designers for system-wide station features including the glass lifts, we were able to make a key contribution to the visual coherence of all the LAR stations.

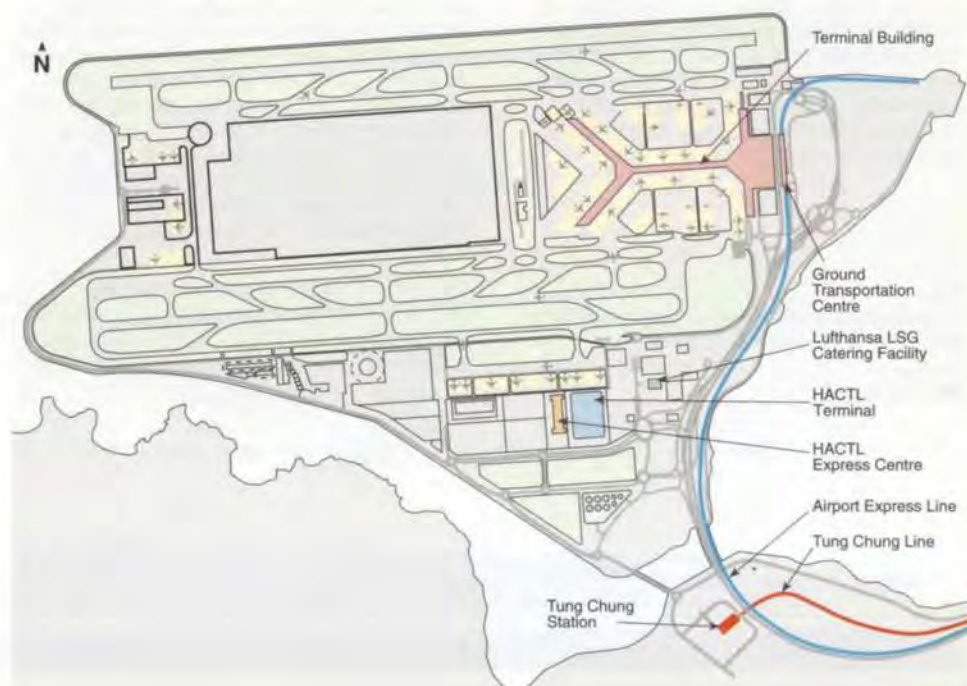
During our involvement in the Airport Core Projects as a whole, around 450 Arup staff from more than 20 offices gave of their best.

Each of the projects described in this *Arup Journal* stands independently as a significant feat of engineering and design. Collectively they represent an outstanding body of work of which we are justifiably proud.

**Peter Ayres
Andrew Chan
Michael Sargent**

Ove Arup & Partners Hong Kong Ltd

2. Chek Lap Kok site plan.



The Airport Terminal Building

Andy Foster Craig Gibbons Martin Manning David Scott



Introduction

By 1991 the Airport masterplan had been developed and this defined the layout of the airport platform including its twin runways, the location and general arrangement of the Terminal Building, the zones for cargo handling, aircraft maintenance, fuel storage, catering, and other commercial activities. In September 1991 the masterplan formed the basis of a competitive tender for the Terminal Building's detailed design, with the additional requirement to develop the architecture of the building as a suitably impressive 'gateway' to Hong Kong.

The design contract was eventually won by The Mott Consortium, comprising Mott Connell Ltd, Foster and Partners, and British Airports Authority plc. Ove Arup & Partners was appointed as structural designer for the scheme design of the superstructure and the full design of all visible steelwork, as well as being fire and acoustic engineers for the building (see pp28-29, 32-33).

The masterplan on which the design contract was based defined the layout of a Terminal Building suitable for an international airport with 35M passengers a year initially, ultimately rising to 87M pa. The plan defined the number of aircraft stands, the principal space requirements, and how the building was to be phased. Its key components comprised the link to the Ground Transportation Centre (GTC), the processing building, the concourses, and the passenger transit system within the building.

1 top:
Aerial view looking west; Ground Transportation Centre and processing building in the foreground.

2 below:
West-east section.

Competition entry

The competition design retained the distinctive plan form of the masterplan concept, but made significant improvements that greatly enhanced the building's architectural character. Three essential strands were interwoven: the functional planning, the engineering, and the need for a unifying architectural concept. For the plan the design team returned to the 'upside down' building concept which had been developed for the terminal at Stansted¹. This put the mechanical engineering plant and the baggage handling installation in the basement and, above that in this case, two levels of passenger areas for Arrivals and Departures. Additional areas for further plant, airline offices, or retail installations were placed on mezzanine levels between basement and Arrivals, between Arrivals and Departures, and above Departures.

The team also proposed the idea of modularity, not only to reduce the number of details to be designed and then learned on site, but also to provide some flexibility for the client to review what he wanted during design and construction, and indeed during the life of the building.

As at other terminals, the enclosure above the Departures level and the walls of the building provided the unifying element to the whole project. At Stansted the structure is a series of independent freestanding trees 36m apart in both directions. At Kansai International Airport², the roof spans the whole width of the terminal. At Hong Kong, the singularity of passenger flow, and also the shape of the building, led to the selection of parallel circular section vaults spanning 36m, based on a diagonal grid sympathetic to the diagonal edges of the masterplan.

The clarity of the design, the modularity, the simplicity of roof concept, and the way in which it responded to the particular shape of the masterplan, were the features that so attracted the client to the proposal at the competition stage.

Concept review

After an appointment in early 1992, the first stage of the project required the team to review the masterplan and develop the outline technical proposals so that the cost plan could be reviewed and confirmed.

Plan

Departing passengers arrive by road or rail at the GTC in front of the Terminal Building and transfer via bridge links to the processing building. Once inside, the check-in desks of the Departures area are accessed via further bridge links across a spectacular Arrivals Hall. Beyond Departures, passengers pass through immigration and arrive at the East Hall, which contains a zone of restaurants, shops, and other commercial activities. From the East Hall, the concourses extend in three directions and provide 38 bridge-served gates for wide-bodied aircraft. Since the building is approximately 1.2km long, an underground train or 'APM' (automated people mover) is located below ground level, connecting the East and West Halls for passengers departing from gates in the distant diagonal concourses. The APM tunnel also provides a route for baggage circulation to and from the baggage hall under the processing building and is extendable to link through to a future phase 2 terminal and its associated concourses.

Arriving passengers follow a reverse route, the Arrivals level being located immediately below Departures. The vast baggage reclaim hall beyond the East Hall is located above the basement baggage handling hall and below the Departures level in the processing building. From there it is a short walk through immigration to emerge at the lower level of the Arrivals Hall.

Diagonal Concourse

West Hall



West Station



Building form and frame

Any airport terminal comprises two fundamentally different sorts of building, that for the processing areas and that for the concourses. The former is deep plan, the latter linear, and the number of levels is different. A comprehensive evaluation of steel and precast, prestressed, and in situ concrete options was made for various grids for both building types and different stability systems.

Processing building

The basement in the processing building was set at not more than 2m below apron level. This was for reasons of ground water, the maximum height at which baggage handling tugs could be expected to manoeuvre out of the baggage hall, and co-ordination with the passenger transit system.

Above this are the two main levels of reinforced concrete frame with an 8m storey height. This structure was designed as unbraced, because of the difficulty of locating bracing reliably within the baggage handling hall. A 12m x 12m grid was selected with a 700mm deep ribbed slab for speed, it being easier to prefabricate reinforcement cages in such a solution. A constant depth structure allowed the use of table forms and plastic moulds, which enhance speed and quality. Joints are provided at approximately 70m centres.

The Arrivals level floor (the roof to the baggage handling hall) is designed to support baggage handling conveyors hanging from it.

The 12m x 12m column grid up to the Departures level and the 36m x 36m roof column grid above were verified as optimum solutions to co-ordinate with the overlaying levels of baggage handling, service mezzanines, and check-in desks.

Concourse

The concourse structure is necessarily different. The passenger transit system has to lie beneath, and so a 6m deep basement was constructed for the whole length of the concourse. This is one of the major early investment items in a new airport; all the sub-ground works have to be built on day one, because it is not feasible to come back later to build new tunnels under a much-used apron.

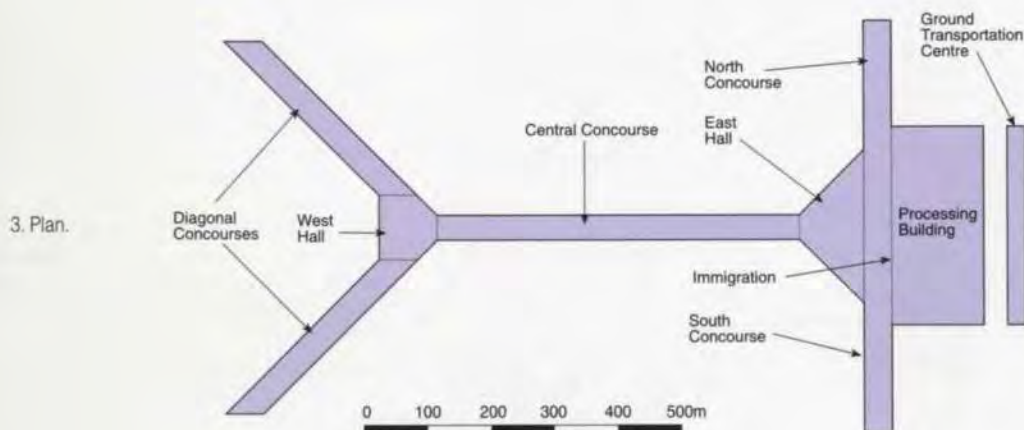
Above that within the concourse is ground accommodation for plantrooms and storage of apron equipment, and above that two levels of concrete ribbed slab on a 12m x 9m grid.

The lower (Arrivals level) slab is 6m above apron level, allowing traffic to pass beneath it, and is approximately at the same level as the threshold of most international long-haul jets. Along the centreline of both Arrivals and Departures levels are travellers to speed up passenger flow.

The Departures travellers are spaced apart to allow light from the roof to penetrate to the Arrivals level beneath.



4. Departures road level.

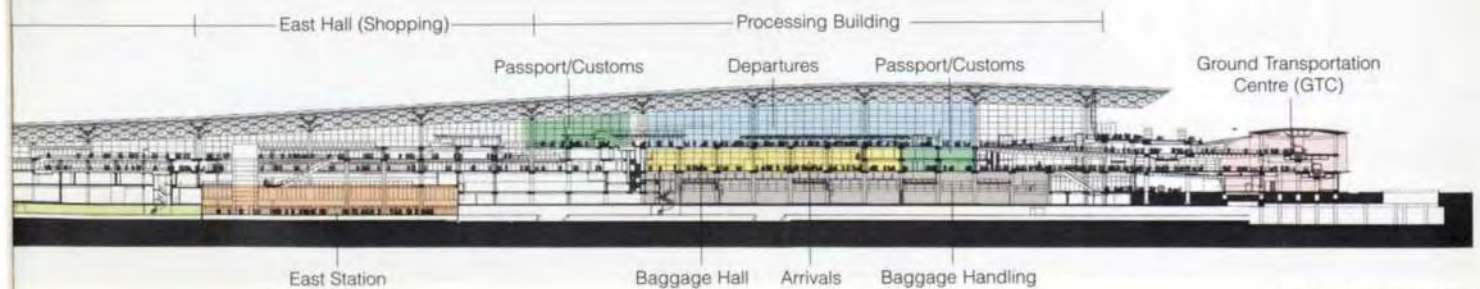


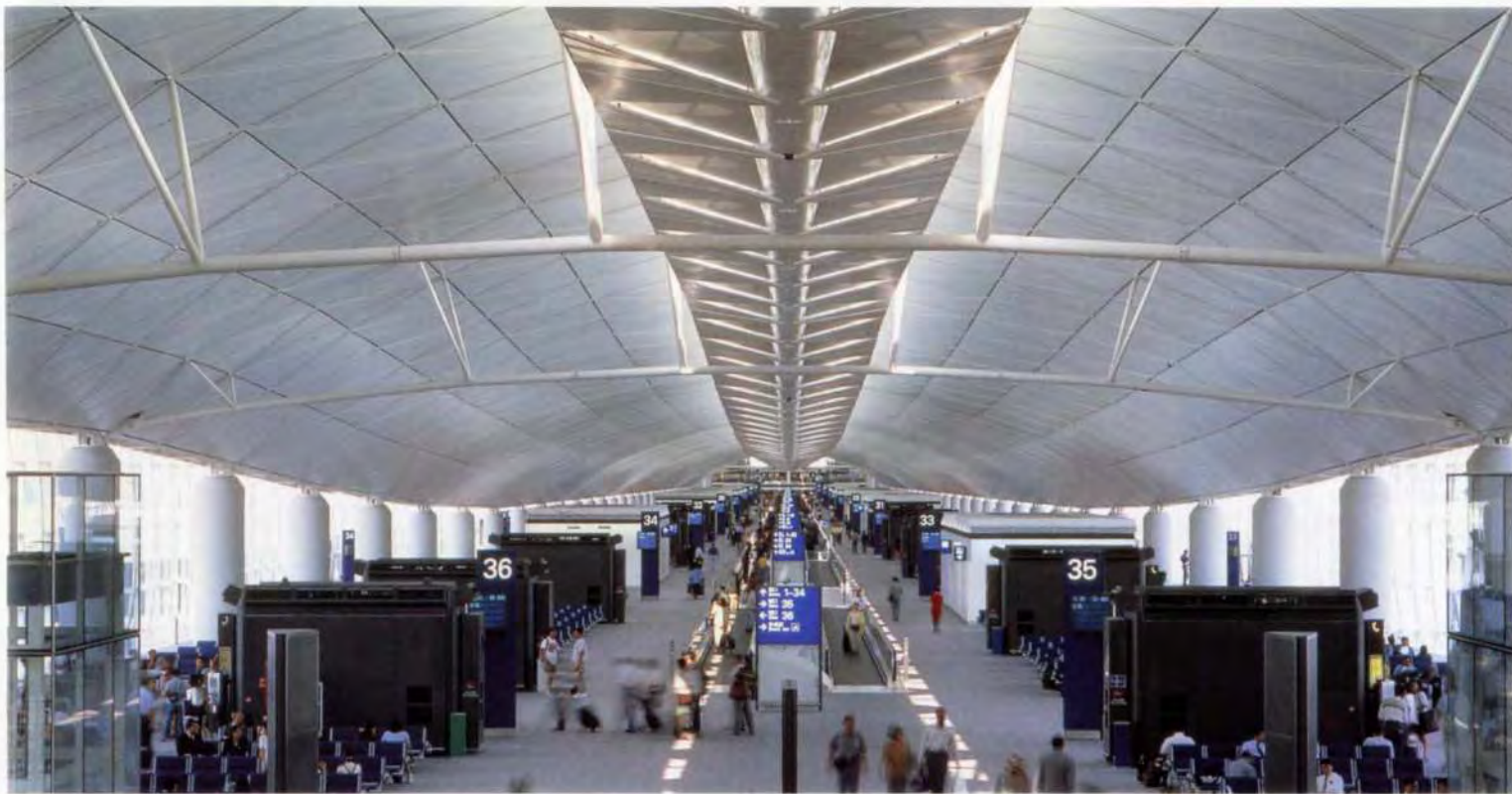
Central Concourse



5 above:
Departures level.

6.
Bridge links to check-in desks on Departures
level above Arrivals level.





7. Central concourse looking east.

The roof

Oversailing the whole Terminal Building, the roof takes the form of a multi-bay barrel vault structure. The vaults are aligned parallel to the direction of passenger flow and are thus helpful for orientation within the deep plan.

Freed from any mechanical services and with the provision of 8% skylighting, the roof becomes a light, bright, daylit canopy beneath which the numerous and varied functions of an international airport can proceed unhindered.

The roof changes in height to accommodate the differing requirements of the activities beneath; hence it is at its most lofty above the processing

building to give a large and dramatic space, and then gently reduces in height above the East Hall and along the Central Concourse before rising again above the West Hall.

Early on in the design a number of key decisions were made regarding the vaulted structure. In the processing building the column grid was set at 36m x 36m with the vaults tied.

In the central concourse the roof was low so ties would be intrusive, and through a combination of increased column stiffness due to reduced height and the ability to close up the column centres to 18m along the vault, it was possible to omit the ties.

8. Baggage hall.



The rise of the vault was studied and at an aspect ratio of 1:6 was found to be tolerant to all the various loading and restraint conditions around the roof. The ties were lifted off the horizontal for architectural reasons, the actual tie rise being a compromise between efficiency and appearance. From the point of view of preventing the vaults spreading, the ties are most effective as horizontal elements; however, when raised off the horizontal they allow the vaults to adjust their geometry with changes of temperature. Hence, there are no movement joints parallel to the vaults, despite the roof steelwork being a maximum of 690m wide.

Although the competition scheme was based on a diagrid solution to the barrel vaults, a simpler parallel arch scheme was investigated. Whilst having obvious advantages in terms of cost, fabrication, and erection, this solution did not work comfortably with the diagonal façades and represented a major down-grading of the architectural quality of the building. Having obtained client confirmation of the desired solution, there remained further basic studies regarding the 'grain' of the diagrid, the type of elements, and their sizing.

The 'grain', or number of elements and nodes per bay, determined the extent of fabrication within the vault and contributed to the sizing of the elements. Several alternatives were studied, but for reasons of time it was impossible to carry out optimisation studies for all areas of the roof. The eventual decision to adopt a 6m grain was based on the resulting architectural scale, simplification of the interfaces with glazed walls, and establishing that there would be no major penalty in terms of steelwork costs.



9. Column / roof vault detail.

10. Ceiling detail.



Geometry

The geometry of the diagonal lattice was chosen to provide constant length diagonal members and constant geometry nodes. The longitudinal curvature was created by cranking straight lengths of vault at grid locations at an angle of either 1.6% or 0.8%, thereby standardising the geometry at the cranks. The transverse curvature was created by simply rotating a standard vault and dropping the roof to the required elevation. A double line of elements was provided along the valley line to accommodate the geometric variations and to permit the modularisation of the roof.

Throughout the early stages, the overall geometry was developed to minimise the cladding area and internal volume. The roof was lowered within a number of pinch-points, found typically at the ends of the concourses, where the clearance to the roof structure is as low as 3m.

Loads

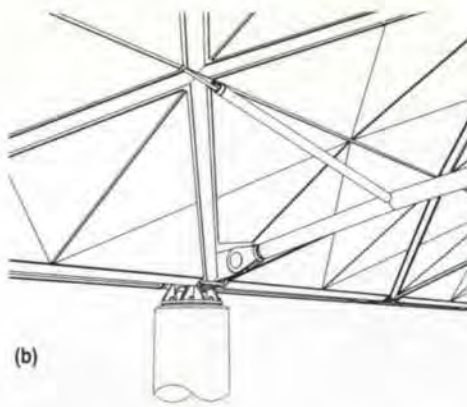
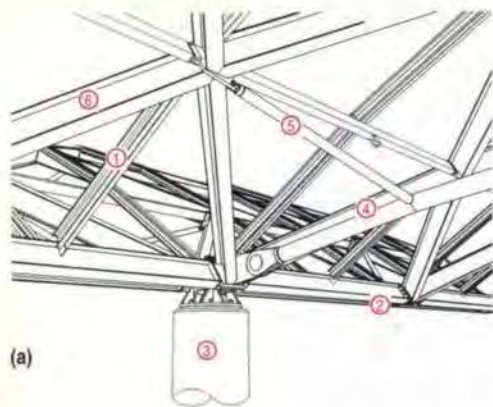
Wind loads were derived from wind tunnel testing and were substantially higher than those required by the Hong Kong code. Very high local suction pressures of up to 7kPa were found at the edge of the roof and wall, caused by large wind gusts travelling across the roof and speeding up in the valleys, thus inducing higher localised suction effects.

Each vault is sensitive to asymmetric loading. The asymmetric wind loads were determined using area averaging techniques where the peak uplift on one side of the vault is measured with corresponding downward pressure on the other.

The size of the roof means that thermal effects are also significant. The provision for built-in thermal forces allowed it to be built at the peak of summer or during the winter months. The predicted maximum temperature under normal operating conditions was 45°C, which might be raised by a further 10°C in the event of air-conditioning failure.

Unusually for Hong Kong at the time, the building was designed for seismic loads. A seismic hazard analysis determined a 500-year peak ground acceleration of 0.12g, and a design procedure was developed based on the New York Seismic Code.

Having determined the basic loading, the next issue was to tailor the combinations to suit the building. Clearly the maximum asymmetric typhoon wind loading would not occur at the same time as the peak temperature, rain ponding, or live loads.



Key

- ① Rolled steel purlin
- ② Longitudinal roof member
- ③ Reinforced concrete column
- ④ Tie
- ⑤ Tie restraint
- ⑥ Diagonal member

11. Perspective of junction between column and roof vault; (a) with ceiling panels removed, (b) with ceiling panels in place.

Analysis

A combination of linear and non-linear analysis was used for the roof structure. Linear elastic analysis of large areas of the roof, including a representation of the concrete support structure, determined the linear elastic movements and forces. Non-linear analysis of individual bays and small sections of roof was used to study secondary effects and vault buckling, whilst global buckling loads were employed to determine amplification factors in accordance with the Merchant-Rankine approach. The amplification factors implied by these studies were then used in conjunction with the linear elastic results for element justification and movement assessment.

Two large models (mega-models) were developed using the Arup in-house program GSA. These covered the areas of the processing building and the diagonal concourses and contained all primary roof elements together with a lateral stability model for each bay of the concrete support structure. Where shear walls provided the lateral restraint they were modelled as simply spring stiffnesses (two translational and one rotational) and where frame action provided stability the frames were modelled explicitly. The roof support columns were modelled with equivalent back spans which incorporated the stiffness of the floor beams framing into them and the variations in column height. Cracked section stiffness properties were used throughout.

All normal load cases were analysed using these models and the resulting design forces were multiplied by amplification factors determined by the non-linear analysis. Amplification factors varied with vault location, magnitude of vault loading, and tie force. Element justification was performed using a post-processor which automatically checked elements to the requirements of BS5950.

The output of the post-processor was linked to AutoCad to allow member utilisation factors to be represented in colour on graphical output of the mega-models. This made it relatively easy to obtain a visual appreciation of the stress distribution throughout the roof.

Buckling

In addition to each element, the structure as a whole is susceptible to buckling, and so it was not possible to verify buckling stability using linear elastic analysis and the conventional BS5950 approach. The vault is continuous, curved, and subject to substantial axial forces and major axis bending. Whilst the effective length of the elements in the plane of the roof is readily identifiable, the concept of element effective length out of the plane of the roof is more difficult to apply. The roof vaults could buckle in a number of modeshapes, each of which has an associated buckling load factor.

Buckling of the roof vaults was investigated with the analysis program Fablon, which uses an iterative approach to achieve full equilibrium and includes secondary effects. Determining the buckling load factor was achieved by performing successive analyses, incrementally increasing the load and monitoring deflections to ensure that equilibrium was reached without gross steps in the load-displacement curve. Overall buckling could be seen in both the displaced shape and steps in the curve. A typical buckling load factor for an untied vault was four times the maximum ultimate downward loading. This implied a major axis moment amplifier of 1.33 for this loadcase. The amplification factors under other loading regimes could then be calculated by comparing average forces in the vault elements to those generated by the maximum load.

Restraint conditions were important when considering the behaviour of the vaults and numerous restraint conditions and loading regimes were studied. Particular attention was paid to the amount of spreading restraint provided to the tied vaults by surrounding vaults and cantilever columns. In the fully 'free-to-spread' condition the vault compression and the tie tension were coupled by the tie hangers, so creating spread, and the buckling load factor was consequently increased. This phenomenon was studied in detail to allow amplification factors for individual tied panels to be linked to tie force.

Detailing the roof structure

Given the repetition inherent in the design concept, the most important connection detail was that at a typical node. Here six elements are joined together - four diagonal Universal Beam (UB) members and two square hollow section longitudinal members. Additional complexity is caused by the node occurring at a crank location in the faceted vault; hence the members do not lie in the same plane.

The solution adopted was to include a 'node plate' at the centre of the connection onto which the diagonals were welded; this also provided 'ears' for the bolted connection of the longitudinals. The node plate was effective in simplifying the geometry of interconnecting elements at shallow angles and could also be extended to accommodate the connection of tie restraint members and other ancillary details.

The column head is a key architectural detail, not just because of the high stresses in these areas but also because of the complex geometrical and architectural constraints placed on the detail. Within the confines of a 1.2m diameter reinforced concrete column top, two 100-150 tonne 36m span vaults of differing positional geometries had to be located, together with electrical conduits and a centrally-placed 150mm diameter downpipe for the siphonic drainage system.

The detail had to be similar for both the typical fixed roof connections and those details where, in the central concourse, the roof is free to slide in the direction of the valley, thus necessitating the inclusion of guided bearings. In addition, being fully exposed, the detail had to be visually acceptable.

The movement joints across the vault were located at quarter span positions and spigot type details developed to allow longitudinal movement of the vaults but transferring vertical and horizontal shear.

The roofing is supported on metal decking oriented parallel to the vault so that it can be easily cranked around the vault. This was covered by thermal and acoustic insulation, a vapour barrier, and a heat-welded PVC membrane. Services in the roof zone were limited to power for a central lighting gantry and minor services such as cabling for CCTV, mobile phone relay, and smoke detection.

Using a fire engineering approach, Arup engineers were able to justify to the local Fire Services Department that a high level of safety could be achieved without fire protection of the roof steel and without sprinklers.

The roof structure is expressed architecturally by exposing the bottom flange of all diagonal UB elements. Within the diamonds formed by these members, soffit lining panels (perforated metal panels with acoustic insulation) are positioned flush with the UB flanges.

At rooflight and valley locations, the full depth of the roof structure is exposed and UB elements are again used to give visual continuity (hidden longitudinal members are typically rectangular hollow sections). Exposing the structure in the valleys also means that the connections between vault, tie, and column head are exposed, celebrating one of the most important structural assemblies of the project.

Cladding

Whilst generous spaces and thus roof heights could be justified in the processing building, for the remainder of the Terminal Building it was desirable to reduce the roof height to minimise the costs of the perimeter wall and of air-conditioning. The north and south walls of the concourses were reduced to 4.9m, but the wall along the processing building provides natural light to the 330mm deep floor plate, and was maintained at 16m high above Departures level. The glazing materials were selected to maximise transparency whilst controlling solar radiation, heat gain, and glare, different coefficients being specified to suit the varying exposure and shading provided by the roof canopies.

The Departure level cladding support structure spans from the upper concrete level of the processing terminal to the roof. As a result of the arch form of the roof, the overall double curvature of the roof, and changes of floor level, the cladding mullions vary in span from 4.9m to 21m.

The mullions were developed as bow-backed vierendeel trusses fabricated from rectangular and circular hollow sections, and are typically set out at 3m centres supporting 2m x 3m glass panels.

12.
The first roof module being lifted into place, December 1995.



13.
Erection of a roof module, summer 1996.



14.
Roof modules in processing building awaiting infill elements and de-propping.



15.
On-site fabrication of roof modules.

For consistency and standardisation, the mullions were fabricated from uniformly sized elements of varying wall thickness. Thus the transoms and webs of the trusses are 120m x 80mm RHS sections, whilst the front chord is a 150m x 100mm RHS and the back chord a 114mm circular section. These were the smallest standard sections that could accommodate the large spans and the typhoon wind loads of up to 5kPa.

The depth of the bow back mullions was set at 1/15th of the span, resulting in back chord radii ranging from 7m to 47m, each mullion being unique for its given height.

This arrangement, together with alternatives, was discussed with potential industry suppliers and fabricators, the consensus being that the extent of the variations did not present a problem given the existing capability for the programming of automated cutting machines.

The mullions are linked in pairs by welded transoms to form U-frames, providing lateral restraint to the circular section back chord. Transoms between the U-frames are connected by a pin with stainless steel retaining bolts onto concealed spigots.

This detail was key to the overall visual appearance and extremely effective on site as it allowed the U-frames to be prefabricated, positioned, and erected, followed by slotting the transoms in place.

Lateral stability to the wall is provided by bracing a 3m wide strip of wall with 16mm diameter rod cross-bracing at approximately 72m centres. Along the north and south concourses, stability is provided by vierendeel action; the mullions in this position have no back chord and are simple thick-walled 150mm x 100mm RHS stick sections. Similarly 300mm x 100mm DRHS stick sections were used for the 7.2m span on the north elevation. These too were standard sections, albeit newly marketed by British Steel.

Resolving the connection between roof and wall was a very demanding design task as the detail had to transfer wind forces from the wall to the roof yet allow the latter to move freely over the wall vertically and in its plane.

The detail was to be designed to accommodate large (175mm) vertical and horizontal movement, generated by the cumulative effects of multiple vaults under vertical, lateral, and thermal loads, in particular asymmetric wind loads on the 51m diagonal edge of the shell.

Having assessed slotted brackets and spigot details, an elegant cast stainless steel armature detail was developed. The vertical movement capacity is provided by a pin-ended arm which allows the roof to move up and down. The lower end of the armature slides along a high strength duplex stainless steel rod. As the armature is set at an angle to the roof, both movements result in a rotation at the joint, accommodated by a spherical bearing on the armature fork around the sliding surface.

Contract strategy

Throughout the design process there was considerable discussion with the steelwork industry, both to inform the industry about the design development, and to solicit feedback on construction and fabrication issues.

Since the steelwork contract for the Terminal Building roof was to be tendered internationally, it was important for the detailing and prefabrication strategies to remain as flexible as possible. To this end the tender drawings provided a fully detailed solution but contained the option of a bolted or welded node solution. In this way the choice of size and arrangement of prefabricated components was left with the contractor.

The opportunity for a bolted solution to the roof structure was provided by the possibility of splitting the diagonals adjacent to the node connection and including flush end-plate moment connections of sufficient capacity. End-plate connections were detailed via schedules for every diagonal element. A fully bolted solution would also give the contractor the opportunity to propose alternatives to the node solution such as castings.

The cladding support structure was tendered on a performance basis as part of the cladding system.

This minimised the owners' risk by having the contractor verify the design assumptions, avoiding any subsequent debate about the performance of the support structure affecting the performance of the glazing system.

However, all element and weld sizes were given to the contractor, enabling the hollow sections to be ordered at the start of the contract, and a very fast design development process. As a result of repetition, the definition of panel types for the framing plans, and the use of component drawings and schedules, it was possible to produce a complete set of fully detailed information on 72 A0 sheets for the 15 000 tonnes of steelwork involved.

Fabrication and erection

The design of the roof steelwork did not impose any restrictions regarding the pre-assembly strategy to be adopted. It was recognised that elements could arrive at CLK in the form of individual components or as substantially complete 36m x 36m units. Interestingly, the successful tenderer proposed a 'super module' concept in which large preassembled modules comprising roof structure, roof finishes, services, and the supporting structure were delivered to CLK on large floating barges.

16.
Cast stainless steel armature detail.



This strategy effectively applied the large-scale modularisation concepts developed in the offshore industry. In the event, a less dramatic strategy was implemented - specifically, roof steelwork (and steelwork for the cladding support structure) was delivered in small pieces in standard shipping containers directly to the island. The individual elements had been cut to the required length and prepared for jointing at fabrication centres in Singapore and the UK prior to shipping. Once on the island, the individual roof steelwork elements were welded together to form 18m x 6m 'truss-like' sub-assemblies on a series of accurately formed trestles spreading some 300m across the on-site fabrication facility. In all, some 107 000 individual elements were required.

Once completed, the sub-assemblies were lifted into the appropriate location on one of seven purpose-made roof module jigs, which effectively provided 'formwork' to enable the lattice shells to be formed. The jigs had to be made to a high degree of accuracy and be stiff enough for the precise form of the constructed lattice shells to be readily repeatable. Having installed all the necessary subassemblies on the jigs, individual linking members were added and welded into position to complete the roof modules, the largest of which was 54m x 36m. The next stage was to lift the modules from the jigs to the adjacent painting facility. This was achieved using a 500 tonne capacity crane with up to 250 tonne 'superlift' facility. The adjacent painting facilities comprised large sheds supported on rails. This enabled the sheds to be manoeuvred directly over a module recently positioned following removal from the jigs.

At this stage the modules were pre-set to the required span and the paint systems, including the finishing coat, applied. Overall, the fabrication facility itself was a huge undertaking, at its peak employing some 700 workers processing 2500 tonnes of steelwork per month.

The modules were transported from the fabrication facility to the site by four *Mammoet* self-propelled, multi-wheeled transporters.

These computer-linked vehicles each had extendable axles which ensured that the supported roof module remained level whilst traversing the undulating site terrain.

The modules around the building's perimeter were lifted off the transporters and placed directly into position on the supporting structure, but those destined for the processing building were too remote for the crane to reach. For these an ingenious self-launching gantry system was used, comprising two 80m x 2.5m deep girders which propelled themselves and the supported module via cables and winches to the required location in the body of the building. The final operation was the in situ installation of the individual infill members which linked the modules in the east-west direction.

Pre-setting the vaults

As described above, spread of the vaults is partly resisted by raised ties connecting the column heads, and partly by flexure of the supporting columns.

The degree of interaction between the tie and the column is defined such that a specified minimum and maximum tie force is to be induced when the vault is at the required theoretical span of 36m. This was achieved on site by adjusting the ties short so that when the vault spread under the action of the load from services and roofing loads, the target theoretical span was achieved and the tie force fell within the required range.

On site, a number of tests were conducted on instrumented vaults to show that the pre-set calculation by the contractor satisfied the above criterion. This involved temperature-corrected calibrated strain gauge measurement of tie bar forces and lateral vault spread displacements.

As described above, this vault tuning exercise was carried out in the painting facility prior to erection.

Adjustment of the span of the vault was achieved after fabrication via two threaded turnbuckles within the tie element. Post-structural completion surveys showed that the final movement of the roof was as predicted, thereby demonstrating that the required flexure in the columns had been achieved.

Conclusion

The design of the Terminal Building was completed within 24 months and tendered in August 1994. The construction contract was awarded to the BCJ Joint Venture in February 1995, and steelwork erection took place from December 1995 to December 1996.

Throughout the design and construction process, the design team, client, and contractor worked to develop the design within clear cost limitations but without losing sight of the objective of creating a world-class airport building which fulfilled all aesthetic and practical aspirations.

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Credits:

Client:
Airport Authority Hong Kong

Design team:
Mott Connell Ltd
Foster and Partners
British Airports Authority plc
Ove Arup & Partners

Main contractor:
The BCJ Joint Venture

Steelwork sub-contractor:
Watson-Nippon Steel

Illustrations:
1, 4, 7, 8, 10: Dennis Gilbert
2, 11, 13, 15, 16: Foster and Partners
3: Jennifer Gunn
5, 6, 9, 17: Colin Wade
12: Kevin Phillips
14: © Airport Authority

17 below: View through glazing towards Lantau.



Cathay Pacific VIP Lounge: 'The Wing'

Michael Tomordy

Introduction

Dwindling passenger loads from the Asian economic downturn have forced many Asian airlines to re-evaluate how they operate and seek new ways to gain competitive advantage - largely through new global and regional alliances and by offering an increased range of service. Cathay Pacific Airways is the flagship Hong Kong carrier and biggest tenant at the new airport, and it has tackled service differentiation by substantial investment in developing its Business and First Class Lounges.

These offer a new concept in airline lounges and unprecedented levels of service to some of Cathay's most important customers.

State-of-the-art information and communications technology has played a key role in creating these innovative, technologically advanced Lounges. Arup Communications were responsible for all aspects of the Lounge IT and communications, including:

- the detailed communications masterplan
- design development to tender stage
- managing the tendering process
- project management during implementation.



1. Above and below: Typical touch screen sequence using the passenger 'Infotainment' network.

As its interior layout and furniture are likely to change, the design gives Cathay maximum flexibility; outlets in an even grid pattern (four every 4m) in the 200mm floor void allow future requirements to be met with relative ease - the basis of a structured cabling scheme.

The strength of the design was highlighted by the fact that though the architectural design and layout of the Lounge changed frequently over the project lifespan, the cabling design needed no modification or re-design.

Furniture

The Lounge architect, John Pawson, is famed for his minimalist style, and this posed additional challenges to ensure that the IT was not intrusive and blended well with the Lounge aesthetics. Close co-ordination was required with lighting, M&E, acoustics specialists and most importantly the furniture manufacturers, B&B Italia in Milan, to ensure that the custom-made furniture had sufficient internal space for the computer equipment, and offered adequate ventilation. All power and communications sockets had to be accommodated internally and hidden from passengers' view. Additional communications and power outlets are also provided for passengers' use - to plug in laptops, access e-mail, or surf the Internet via a high-speed link.



Arup's key input was to the communications cabling and services distribution, design of furniture and reception desks, flight information display network, and - most excitingly - a new concept in passenger personal entertainment and information systems.

Structured cabling

Adequate cabling is vital for any telephony or computer installation. The Lounge design was based around the distribution and adaptability philosophies of many high-grade office buildings, utilising UTP Category 5 cables for floor distribution and optical fibre cabling in the backbone that fully interconnects the three equipment rooms. Maximum resilience was thus achieved - if one room or cable failed, services could still be provided via a different route. The Lounge's level of IT and communications systems would be the envy of many an office.





2. Open Lounge.

'Infotainment' network

The major IT element is a state-of-the-art, unique passenger 'Infotainment' network, based around a networking technology known as ATM.

This provides high-speed switching between the multimedia sources - video, graphics, text, and audio - used in this system. The network was designed to carry information and entertainment to Lounge users, unlike an office computer network with its typical word processor and spreadsheet packages.

Passengers use the system via a customised desktop unit resembling a laptop. Like the furniture, it was specially designed in the UK to match the unique technical requirements and special furniture aesthetics. Passengers access the services via a touch screen, after swiping their boarding passes in the built-in boarding pass/credit card reader. This immediately personalises displays to passengers from their records stored in a customer database. The passenger sees a customised Graphical User Interface (GUI) that allows him/her to access various menu levels. At the touch of a screen they can get flight information, watch up to 11 TV channels, obtain the latest share price information from Reuters, or perhaps listen to music from a CD juke-box.

Looped video material, similar to in-flight entertainment, is also provided. Though passengers usually stay only briefly in the Lounge, those with transit stop-overs or delayed flights will continue to be occupied and provided with information and entertainment services not available in any other airport Lounge at present.

The challenge of many users simultaneously watching a variety of bandwidth-hungry and time-delay-sensitive material required Arup to plan two parallel networks - an ATM data network for computer-generated material, and an analogue, baseband network for live TV, video, radio, and audio. The analogue network ensures synchronisation between what is displayed and the audio track.

Being able to offer a personalised service is a very powerful feature and a key aspect of service differentiation. For example, each passenger can get a screen message that their flight is about to leave, plus a map of their gate location.

The potential applications are numerous, from passenger-specific marketing / advertising or programming material to gathering valuable market research on passenger habits. For example, the display could tell a passenger: 'The last time you were in the Lounge you watched "Let's Play Golf" Lesson 1. Would you like to watch Lesson 2 now?'

Perhaps the system's most impressive feature is the 'Video on Demand' (VoD) capability. Unlike on-board entertainment where videos are looped and passengers have no control over watching a particular programme, VoD can be likened to the functionality achieved with several VCRs.

As with a dedicated VCR, passengers can start/stop, rewind, pause, or fast-forward programmes whenever they wish, all by touch screen control. The major difference is that the programmes are stored digitally and there is no bank of VCRs.

A key feature of the system is its adaptability. In terms of future applications, the sky is literally the limit. Potentially, if VoD arrives on-board aircraft, passengers can



3. The Long Bar.

watch part of the programme in the Lounge and then at 9000m fast-forward to the cliff-hanger where they had to leave it! Via the boarding pass swipe, advertising can be tailored to passenger profiles.

Electronic shopping is increasingly popular and could be on the system; duty-free goods could be ordered and paid for in the Lounge (using the boarding/credit card reader) and delivered to the destination. Whilst increasing the level of services offered to passengers, these are also revenue-generating products for Cathay.

In this project, what complicated the solution - apart from a very tight schedule - was the balance Arup had to achieve between implementing a largely unique state-of-the-art solution, and ensuring that its components were tried and tested, since very high reliability was vital. Unlike those who use office systems, this network is used by Cathay's passengers, their prime source of revenue. Failure of the network could push customers to other airlines. This placed a far greater level of importance on the network performance, hence the provision of two parallel networks and a resilient cabling scheme.

Passenger information displays

A good example of how technology can assist in architectural design was the use of the latest flat screen technology. 42in displays resembling paintings were mounted within narrow partition walls since conventional cathode ray tube displays were too large. Added advantages are their low power consumption and high resolution, as well as the very modern hi-tech image. These monitors cyclically display TV, customised flight information (Chinese and English), Reuters financial data, and other video-based material.

Compared to the somewhat static, uninformative FID displays used in the past, this is a major leap forward, achieved through a client-server architecture with the source material located centrally and able to be switched to any display at any time, rather than each display containing only one type of material. Traditionally the communications feed is achieved by laying a dedicated co-axial cable to each display. Arup's innovative solution utilised the existing copper-based structured cabling; displays can be relocated quickly to any

location in the Lounge and costs reduced through using the existing cabling infrastructure.

Another service differentiation is the provision of cordless telephone handsets for calls to be made or received anywhere in the Lounge. The usual humble pay phone may be a bastion of simplicity and low-tech, but this Lounge is provided with several touch-screen kiosks with a variety of extra features including fax, document scanner, and socket for laptop connection. These kiosks are multimedia information units, able to display promotional material and revenue-generating advertising (but to reassure technophobes, most of the pay phones are the traditional push-button variety!)

Providing all these systems had a substantial price tag, and the Asian financial crisis meant that Arup had to consider ways of cost-cutting and encourage schemes for revenue generation. Through co-branding and sponsorship from the Lounge IT suppliers, significant cost savings and additional unforeseen sources of on-going revenue were generated. For example, long-distance calling-card companies were allowed to have their logos displayed on speed-dial buttons on the 'house' phones and Hong Kong Telecom displayed their logo alongside Cathay's on the desktop unit screens.

Credits

- Client:* Cathay Pacific Airways
- Architect:* John Pawson
- Communications consultant:* Arup Communications
- Project manager:* Denton Corker Marshall
- M&E sub-consultant:* Mott Connell Ltd
- Furniture designers:* B&B Italia, Milan
- IT contractor:* Hong Kong Telecom
- Illustrations:* Courtesy Cathay Pacific Airways



HACTL SuperTerminal 1

Jim Daly Kieran Flynn Mike Harley Armstrong Yakubu, Foster & Partners



Introduction

Hong Kong Air Cargo Terminals Ltd (HACTL) SuperTerminal 1 (ST1) is the largest and one of the most technologically advanced cargo handling facilities in the world. With the Passenger Terminal, it will help maintain Hong Kong's status as a key centre for international communications and commerce in South East Asia. ST1 is also one of the largest commissions undertaken by Arup with Foster and Partners - the design and supervision team for all the civil, building, mechanical, and electrical works.

Arup's involvement with HACTL's air cargo developments began in 1983 with the firm's appointment by the specialist air cargo systems designers Breier Neidle Patrone Associates as engineers for an extension to the original Kai Tak Terminal - providing the same throughput but in half the building volume. (Incredibly, Arup was discovered via Yellow Pages.) Thus began a 15-year relationship with HACTL.

In 1988 HACTL appointed Arup directly as lead consultant for the building design of HACTL Terminal 2, on the perimeter of Kai Tak near HACTL Terminal 1, providing 750 000 tonnes' extra annual throughput and doubling HACTL's operational capacity. Lack of suitable land meant using a site 40% that of Terminal 1 for a facility of the same capacity. Working closely with HACTL and the cargo handling systems contractor Mannesman DEMAG, Arup designed a seven-storey building housing a fully automated container storage system (CSS) on two levels to a total height of 50m, augmented by a central automatic bulk storage system (BSS) serving all levels in the terminal. The project was completed within its US\$154M budget and five months ahead of schedule; Phase 1 operation commenced before the April 1991 target date.

In spring 1992, Arup was invited to start planning, with HACTL's in-house team, a new air cargo terminal for the replacement airport at Chek Lap Kok (CLK). Initially this was speculative, with formal appointment dependent on Board approval.

Until the dramatic downturn in most Asian economies, Hong Kong's passenger traffic and air cargo was increasing annually by some 10%. In 1992, when the economy was still buoyant, there was effectively a local cartel between four operators for all containerised sea cargo, and the HK government decided to promote competition for air cargo. Six companies responded initially but soon lost heart, and the competition reduced to HACTL (2.6M tonnes throughput) and AAT, a Singapore consortium (400 000 tonnes). After prolonged negotiations, HACTL signed with the Provisional Airport Authority (PAA - subsequently the Airport Authority of Hong Kong (AA)), for stipulated completion on 18 August 1998. This was four months after the original airport target opening date of 1 April 1998, and six weeks after the actual opening on 6 July 1998.

Because of the uncertainty at that time, the HACTL Board had only been willing to place design-only contracts with the two cargo handling contractors (DEMAG and Murata) and a 50 000 tonne order with British Steel for Grade 55C steel piles. There remained much to do in an uncomfortably short time.

Though they met fully HACTL's operational requirements, the Kai Tak Terminals were essentially functional warehouses. For CLK they wanted much more - a flagship building which significantly enhanced the working environment, and which related adequately to the handling systems it housed and, just as importantly, to the Passenger Terminal. The choice of architect to develop the basic concept was obvious to some, but Arup's percentage fee agreement mitigated against this. Invitations were sent to three international and two indigenous practices, asking them to identify the extent of services in the RIBA Plan of Works they could provide for a certain percentage fee.

Foster and Partners made the most attractive proposals and were appointed as Arup's architectural consultant.

The concept

Planning air cargo terminals is determined primarily by the process of moving cargo. As Anthony Charter, HACTL's Managing Director, observes: 'Our business is simple. We take small boxes (for export) and put these into larger ones, and the reverse for import!'

Long before the agreement with the AA, Arup had been working with HACTL's planning team to establish the fundamental process design strategy.

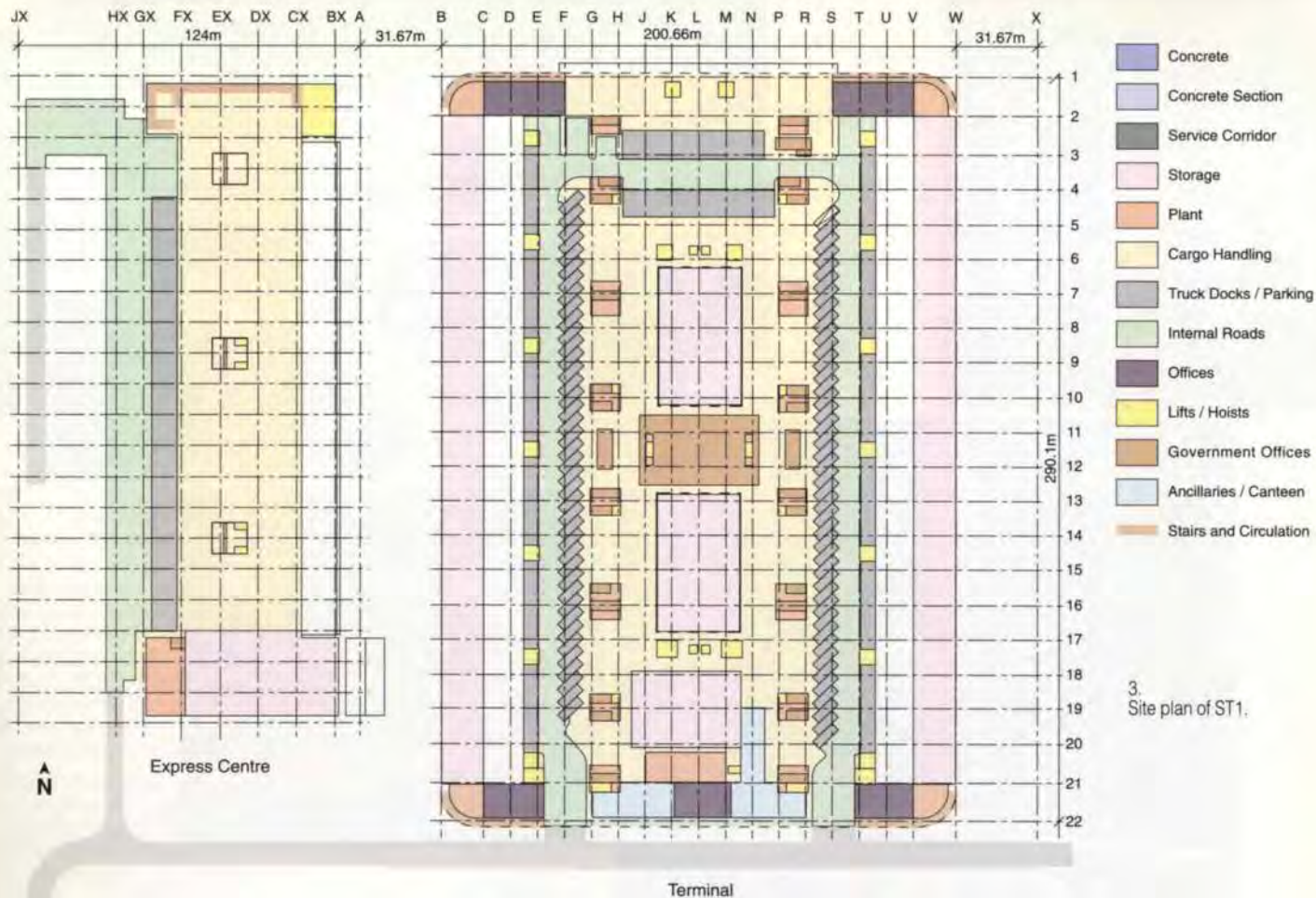
ST1 is two buildings: the Terminal, a six-storey cargo handling facility, and the Express Centre, a dedicated express cargo and courier operating facility. Together they can handle 2.6M tonnes pa of cargo, over twice London Heathrow's 1997 throughput via 16 airline warehouses.

ST1 plays an important social role for its employees and their families, with a huge range of recreational facilities including a fully equipped 1500m² sports centre with three squash courts, badminton courts, a swimming pool, tennis and basketball courts, a jogging track lacing through the landscaped roof garden, and locker room and shower facilities for all staff. Along the building's southern edge is a roof-level canteen with executive dining terrace looking onto the roof garden. At the building's heart, a triple-height glazed atrium - arranged around internal lift cores containing exhibition space at roof level and a large staff common room below - brings natural light deep into the building. All these amenities reinforce the principle that incorporating leisure elements into the workplace can help people enjoy their work environment, and consequently their jobs.

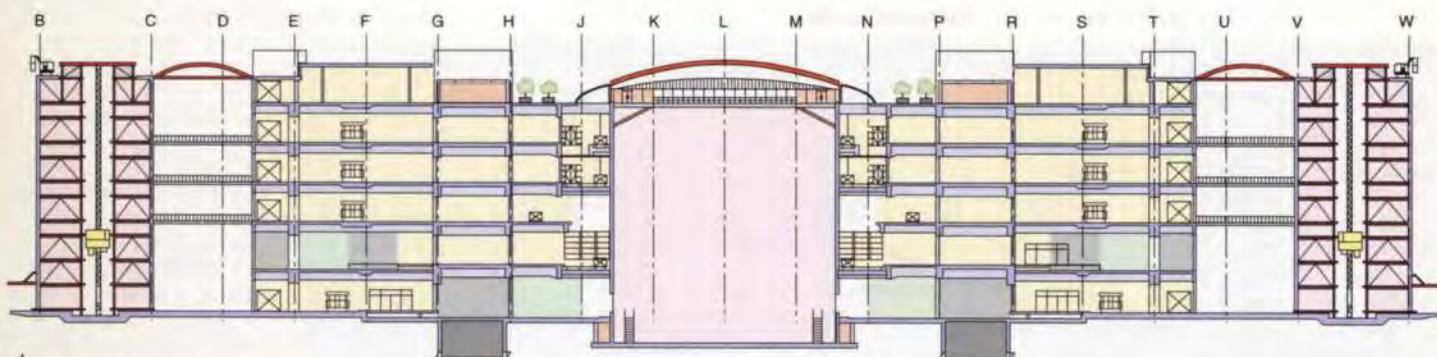
1 top:
South and east façades of ST1.

2 below:
West façade, showing
profile of Express Centre roof against the Terminal.





3. Site plan of ST1.



4. Cross-section through Terminal.



5. Computer-generated image of part of the Terminal, showing (l-r) stand-alone container storage (CSS), 'roadway', operations and truck dock levels.

The Terminal

The six-level, 200m x 290m Terminal processes air cargo containers for international trade. Fully computer-controlled by HACTL's own systems, the building acts as a giant conveyor along which robot stacker cranes lift, pigeonhole, and store cargo, enabling it to be unpacked and processed through Customs and Excise before getting onto lorries for delivery. The Terminal has 240 000m² of operational, office, and ancillary space.

Operationally, it was developed like an onion, with the two central BSSs at its core. Operations and processing run mostly east/west and west/east. On the east and west façades, 260m-long CSSs (steel-framed racking structures accessible on two sides) pigeonhole export cargo containers ready

for processing. The cargo then passes via bridges to the warehouse floors where it is unpacked and converted to bulk and vice versa. The bulk cargo is then placed in 'bins' (steel mesh cages where cargo is held on a consignee basis) and stored in the BSS. Bulk cargo distribution systems on Levels 1, 3, and 4 - a total of 130 automatic bin carriers - transfer import cargo into the BSSs, link each BSS, and transfer cargo between parts of the operational levels to the central Customs and Excise Hall. This is between the BSSs on Level 1 before onward transfer to the bulk cargo truck docks, also on Level 1. The process is reversed for export cargo.

The ground and first floors at the building's north end house a perishable goods handling centre, adjacent to the airport apron to minimise the distance between aircraft and the centre's truck docks. Automated cargo hoists transfer goods to the first floor (doubling the perishable handling area and its associated truck docks), and to the 3600m² of large-scale industrial cold-rooms and freezers on the second floor.





6. Stacker crane within void between CSS racking, from roof level.



7. Roadway viewed from upper bridge.

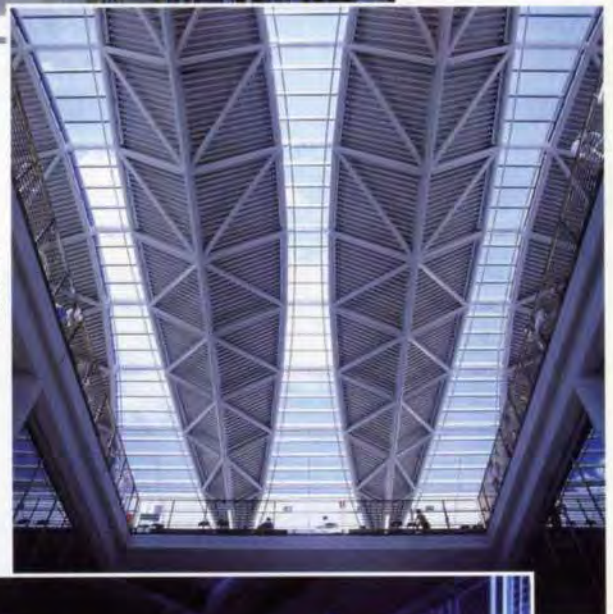
HACTL's central computing system identifies any item of cargo as soon as the inbound aircraft leaves its country of origin and tracks it until it is collected. Offices along the fully-glazed north and south façades around the operations core provide some 12 000m² of space for HACTL staff, airline representatives, government departments, banks, and recreational facilities. The basement houses all major plant areas including fire services storage tanks and pump rooms, seawater-cooled chillers and pumps, plumbing water storage tanks and pumps, eight 4.5MVA substations, and three 1.5MVA diesel-driven standby generators.

Also in the basement are the main north/south services distribution corridors which serve the primary vertical cores.

The Terminal's visually striking features are the blue steel structures throughout the CSS and the BSS. It is important to remember that, unlike sea cargo containers with their inherent structural strength, lightweight air cargo containers or pallets have virtually none. When moved in any direction, they must be continuously supported. In the Terminal this is done by powered roller decks, right angle decks / turntables, and castor mats incorporated in all container-moving machinery - and all supported by the blue steel structures. The actual machinery is always painted yellow.

A key design feature of the Terminal is the CSS arrangement. Each CSS is essentially a stand-alone structure, giving the commercial advantage (in a very tight programme) of being buildable separately, thus enabling testing and commissioning of the CSS system while the rest of the building was still going up. The CSS' 16m separation from the building creates roadways - primarily for dolly access as well as for firefighting vehicles - in what is a very deep building. The efficiency of an air cargo terminal is determined by its number of points of airside cargo access; the better the access, the more cargo that can be processed simultaneously. Separating each CSS from the main building creates six lines of airside interface instead of two, which is why the Terminal has a unique airside interface length approaching 2km. The roadway roof is made of steel 'butterfly wing' trusses clad with weatherproof louvres, which add natural ventilation in the non-air-conditioned parts of the building.

Glazed rooflights spanning between the trusses bring natural light to the dolly roadway and warehouse floors. The glazed façades of each CSS are open at low level along their entire length, drawing make-up air through the (internally unclad) CSS and venting it through the louvre system. Heat from the high level motors driving the stacker cranes and powered roller decks is vented by high level louvres in the CSS cladding.



8. Butterfly wing roof trusses over the centre of ST1.



9. Stacker cranes operating within BSS.

The resulting space is dramatic - close to 300m long, 16m wide, and 45m high, it became known as 'the canyon' to the design team... and there are two of them! They create a weather-protected airside interface, give fresh air and natural daylight to the heart of the building, and also give HACTL the best possible advertising as the glazed façades expose the CSS to public view. Cost studies showed the capital cost of the roadway roof to be less than weather-protecting the internal façades of each CSS, the internal façades of the warehouse core, the link bridges, and the low-level canopies for the airside interfaces.

With a warehouse floor plan of 260m x 140m, daylight awareness and an enhanced working environment were fundamental to the building design. The BSS roofs are similar in construction to the CSS. They provide natural daylight to the core of the operations floors, the rest areas like the central 'tea room', and the exhibition space on the roof. This, with air-conditioning of the warehouse floors, and the daylight through the CSS roadway roof and the CSS glazed cladding, greatly enhances the work environment in what can be very labour-intensive areas. In the truck dock areas there is a dedicated exhaust fume extract system at every position. Fresh air is also provided mechanically to ensure that air supply, comfortable air movements, and temperatures are maintained in the non-air-conditioned area. These fans double for smoke extract in a fire.

The full double-glazing of the north and south offices' façades meets stringent acoustic (against aircraft noise) and insulation criteria whilst achieving high levels of light transmission. The outer panes are of clear laminated solar control glass, reflecting 70% of heat energy and giving 80% light transmission. Inside the 200mm cavity are horizontal movable blinds, which reduce glare and help lower the shading coefficient of the whole system to a remarkable 0.39.

This performance matches reflective laminated glazing, which allows less than 25% light transmission. The offices are cooled by ceiling-mounted chilled water fan coil units. The ceiling acts as a return air plenum with the return air extracted through the light fittings. In larger areas like the canteen and sports hall, central air-handling units (AHUs) on the roof are used.

The south block is basically high quality speculative offices, housing airline representatives, the only Hong Kong and Shanghai Bank in CLK, and a 3500m² canteen and kitchen. The kitchen operates round the clock and can serve 900 meals six times a day; the canteen mostly serves shift workers and so has to serve the meals during a one-hour window. Also within the canteen are a Western restaurant and an executive dining area which opens out onto the landscaped garden. The north office block houses HACTL offices and the sports centre. This is fully glazed, with stunning views of the passenger terminal, the runway, and the Kowloon peninsula mountains.

A large building creates a large roof. Although the Terminal roof mostly houses plantrooms and empty container storage areas, it still offers 10 000m² of space for the 25m heated and cooled outdoor pool, the tennis, basketball and five-a-side football courts, the barbecue areas, and the jogging track, all set into the landscaped roof garden with its flowering mature trees and various indigenous Hong Kong flora blooming at different times of the year. The various structures of the BSS and CSS roofs also add to the landscape, and the BSS roof opens up here to create the exhibition hall. This exhibits models showing how the building functions and also lets visitors view the very impressive BSS spaces.

The Express Centre

The two-level, 200m x 90m Express Centre provides a gross floor area of 50 000m² and can handle 200 000 tonnes of cargo pa. Its primary role is to give express cargo and courier operators their own dispatching and sorting facilities and offices.

The curved roof structures are the most expressive parts of the building. The initial steel design was replaced by a twin-skin concrete solution that did not suffer from the same condensation/corrosion problems and was built at a lower price; these roof structures reflect the Express Centre's division into seven bays on each level. The north bookend bay houses HACTL's own ramp maintenance facility with associated training rooms, offices, rest areas, and changing rooms. The south bookend bay contains an automated 6.1m container storage and handling system for large consignments like Grand Prix and luxury cars, as well as larger livestock like racehorses, elephants - and the odd killer whale! Immediately south of the north bookend is the strongroom area, with four airside and four landside armoured truck docks and a central high security vault for processing high value consignments, eg diamonds, cash and gold bullion.

10.
South façade of Terminal.





11. Entrance to dolly train lift in Express Centre (right foreground).



13 above: West façade of Express Centre.



12. West façade of Terminal, showing exterior of CSS.



14. Detail of Express Centre.

A typical bay comprises an operational express warehouse floor, some 36m x 45m in extent, with a service core centred to the side and shared with the next bay. Fully-glazed offices are located on mezzanines above both levels arranged around the service core. Continuous rooflights across the building separate each pair of bays from its neighbours. Goods lifts in the service cores link the operations floors to a central Customs and Excise Hall on the ground floor mezzanine.

As in the Terminal, the Express Centre has full disabled persons access, provided for the Level 1 mezzanines by inclined wheelchair platform stairlifts in each core.

Express cargo handling is very labour-intensive and straightforward. Import cargo is delivered to the east face of the building on each level, and processed in the main operations areas before being transferred to the truck docks on the west face for onward delivery. Two-level operation is made possible by two large hydraulic lifts that can raise fully-loaded 20m long dolly trains (equivalent to a 40ft container truck); the lifts are enclosed in a fully-glazed shaft.

The operations areas are naturally ventilated; the east and west façades are open at low level (protected with typhoon shutters) and glazed above.

The roof is insulated by its naturally-ventilated double concrete skin (which also incorporates drainage and concealed high-level lighting). The exposed sprinkler and drencher system fire service pipework curves to match the profile of the concrete.

The mezzanine offices are air-conditioned, and cooled in the same way as the Terminal offices; AHUs within the cores leave the profiled roof structures free of ductwork. The building is mostly glazed to maximise daylight awareness and to expose its multi-functional nature to public view - as with the whole complex.

External works

The elevated road which links and accesses Level 1 of both buildings complements their structure, using forms carefully designed to prevent unsightly drip stains and generally to minimise visual impact.

The parapets incorporate planters to further soften the visual impact. In the external areas generally, truck and car parking and roads are all incorporated into landscaped areas planted with flowering trees and shrubs.

Foundations

The original main island had a peak of 121m, which was systematically blasted away leaving only its spur of Pak Sha Tsui in the south east corner of the reclamation still proud above reclamation level. This spoil, supplemented with marine sand and brought in massive 100 tonne tipper trucks, was used as fill for the new airport.

Worryingly, the spoil frequently contained large granite fragments up to 2m in diameter, very different from the stated 300mm graded down quality.

This was important, since in view of available plant and time constraints Arup believed that heavy duty steel H-piles would be the foundation system.

The likely presence of such large rock fragments questioned the wisdom of this. A further problem was that although PAA had tried to dredge most of the marine and alluvial deposits, this was unlikely to have been completely successful, and significant settlement of the fill and resulting negative pile friction were likely. With the client's approval, a trial pile-driving contract was negotiated using the heaviest available universal bearing piles (305 x 305 x 223kg/m) in Grade 55C steel. It was calculated that this grade would offer at least 10% price advantage over the then statutorily approved steel pile grade. The object of this test contract was two-fold; to evaluate drivability of the steel H-piles in a suspect site and to gain formal government acceptance of this higher steel grade.

The latter was achieved, but the 12 successfully test-driven piles though were statistically too few to fully satisfy concern about encountering undrivable boulders.

A further problem was fill settlement, and its effect on road and apron pavements. Clearly this was nothing like what had occurred at Kansai Airport's artificial island¹, and comfort could be gained from the fact that a two-year construction period would ensure that by the time the (Airport) apron, roads and external works were installed, perhaps 70% of final settlement would have occurred. Geotechnical engineers are understandably cautious, and their predictions required allowance for further settlement up to 200mm. A flexible pavement that could be made good relatively easily where settlement did occur was clearly an attractive solution. PAA had decided on *Pavlok* interlocking concrete blocks, which appeared sensible, but HACTL were not convinced that the surface would be smooth enough for their dolly trains - diesel / LPG driven tugs pulling up to six solid-wheeled unsprung trailers. Also, main utility connections to and from the building were fitted with a series of 'rocker' joints to accommodate differential settlement.

Fortunately, the client was convinced by a series of entertaining tests using dolly trains with empty containers at a marshalling area in a sea-cargo container facility. The great advantage of *Pavlok* over, say, a macadam surface, is that settlement can be made good locally at minimal cost and, more importantly, with insignificant disruption to cargo operations. This still left one major problem, however. At the airside interface where the dolly trains deliver (or receive) containers to the container handling system, they must be either horizontal or preferably lean at 1:100 towards the Terminal. The solution was to provide a 4m wide cantilevered slab extending from the Terminal for these interface locations, and to use either transition hinged slabs or *Pavlok* paving beyond this.



15
Truck dock area in Terminal.

Structure

Structurally, the Terminal is relatively simple. Cargo-handling and truck-docking requirements dictated a 10.5m x 13.5m planning grid, enlarged in two areas to 21.0m x 13.5m to accommodate road traffic manoeuvring needs.

From early on, Arup aimed to integrate the structure with the M&E systems, incorporating smoke extract / ventilation / air-conditioning ducts to minimise the building's overall height. Much time was also spent developing acceptable column head / beam details, and minimising structural depths and concrete quantities. One problem encountered on the Kai Tak Terminals had been impact-induced stress cracking of the concrete slabs. Fork-lift operators should lower loads gently onto warehouse floors, but most drop them from well over 150mm. The solution for ST1 was to provide top and bottom anti-crack steel and to design slabs (but not their supporting structure) for 25kPa wherever fork-lift traffic was anticipated. Generally, 40N and 60N concrete was used for horizontal and vertical structural elements respectively. The basement to the south of the Terminal is ground-bearing, and to allow for relative settlement with the piled Terminal building, is connected by two fully articulated connecting services corridors.

The most obviously glamorous parts of the structure are the steel roofing systems over the CSS roadway, the two BSSs and the exhibition area. After prolonged negotiations with the Hong Kong Fire Services Department (FSD) it was agreed that the steel roof over the CSS roadway would have a two-hour fire rating. For the architect's delicate butterfly wing truss concept, intumescent paint on the relatively slender members clearly could not provide the necessary rating, and cladding them with fire-rated board would be singularly unattractive. The only possible solution appeared to be a water-filled tubular system, but clearly the thermal capacity would be inadequate unless the water was circulating. The solution proved simple and elegant: provide sprinklers in the steel tubular structure itself, and connect the whole system to the fire service drencher system. In the event of fire, any activated sprinkler would go on receiving cold water, ensuring that surrounding steelwork remained well below 550°C.

The idea seemed sound theoretically, but the client and a very sceptical FSD had to be convinced.

At the time Arup was reviewing the tender for the Terminal roof steelwork - including the CSS roadway roofs - from Seele Hong Kong, who had already established a reputation for the successful use in Germany and Austria of water-filled tubular steel structures for hot water heating systems in large glazed façades. The parallel was clear, and after brief discussions with the enthusiastic Seele, a quotation for two sample butterfly wing trusses was agreed by Anthony Charter. Arup Fire made arrangements with the UK Loss Prevention Council (LPC), and two units were shipped to Darlington in April 1996, where they were tested and witnessed by LPC and Arup (see Fig 5, p29).

The tests were completely successful - even with the full propane gas fire load, the water temperature in the butterfly wing trusses couldn't be got above 40°C. The system was an inefficient water heater, and FSD's acceptance appeared likely. There was, however, one further obstacle - corrosion; despite Arup R&D's assertion that without oxygen there could be no corrosion, FSD were not impressed. The pragmatic solution was to look at samples of existing pipework in the original Terminal 1 (now over 20 years old): corrosion was virtually unmeasurable and FSD approval was obtained.

The CSS roadway trusses comprise a single bottom chord and two top, acting as a vierendeel with buckling of the top chord restrained by three horizontal 'purlins' between each butterfly wing. The design of the CSS racking structure itself (a separate commission by DEMAG) could adequately resist typhoon / seismic loading-induced moments, but the resulting deflections would have caused unacceptable distress to the external glazed CSS façades. To temper this movement, the CSS roadway trusses were designed as props, transferring the CSS wind / earthquake loads to the main Terminal structure.

The structure over the BSSs, spanning 33m, did not have to be fire rated as it was above a fully-automated unoccupied area, where the public or FSD personnel could not be at risk. Its roof system has a curved bottom chord and is framed conventionally. For architectural reasons the supporting columns are quite slender, and not able to resist the arching thrust of the trusses; to counter this the trusses are fixed at one end, with Glacier sliding bearings at the other.

Depending on operational or recreational requirements, various surface finishes are provided for the horizontal flat roof itself. Essentially, the roof structure is 'upside down'. Directly above the concrete is a liquid-applied membrane (HLM 5000), then a slip membrane, insulation, lightweight screed to falls, sand levelling, and the applied precast concrete / brick finishes. Jeene waterstop systems (developed in Brazil and manufactured in the USA) were used for all roof level expansion joints, and for certain roadway / truck dock locations on Levels 0 and 1.

The Express Centre, though much smaller than its sibling, is architecturally perhaps the most exciting part of the development. Being primarily labour-intensive, the container handling systems had minimal requirements, giving much freer range to the design team's creativity. Foster's inverted barrel vaults add a brilliance to this facility which a more pedantic and economic approach could not have achieved. The client, however, was not easily convinced, and various schemes - including a steel solution that suffered from potential internal condensation / corrosion problems - were addressed and costed. Fortunately the original concept won the day and the elegant, seemingly light and dynamic, solution was adopted.

Fire engineering

After the constraints of the cargo handling system and the road traffic requirements, this was the next most important design criterion for the whole development. In view of the extremely dense population figures, and the firefighting problems encountered in high-rise buildings, the Hong Kong FSD are understandably conservative. Without the input of Arup Fire, ST1 would have looked very different and cost the client far more.

The gross floor area of each Terminal level is 58 600m², and the total enclosed building volume well in excess of 2Mm³. HK FSD have adopted the pragmatic approach that 28 000m³ (1Mft³) is the maximum volume that can be successfully addressed by a firefighting team. Each such volume needs to be physically separated from its neighbour, either by a two-hour fire-rated wall / fire shutter, or by a continuous drencher water curtain - essentially (and theoretically) to contain all fire and smoke emissions.

The very nature of air cargo operations requires uninterrupted space and this concept is most important in the CSS and BSS areas where volumes are well in excess of the prescribed provisions. Fortunately precedents had already been established on Kai Tak Terminal 2, which had automatic cargo handling systems with no operating personnel and only short, transient activities by small maintenance teams.

Each CSS, with a volume over five times the normally permissible, theoretically needed protection from adjoining facilities by a two-hour fire-rated separation. This entailed two-hour fire-rated protection to the steel CSS roadway canopies (sic) and to the steel CSS inter-link conveyor bridges - in reality a relatively small price to pay in view of FSD's original requirement for a two-hour fire-rated structure for each CSS, which would have caused the client additional expenditure of \$30M. Essentially, Arup Fire's argument was based on the assertion that the main operational building (ie excluding the north and south offices) was contained within the area E-T/2-21.

To meet Building Department and FSD demands, emergency vehicle access to Levels 0 and 1 had to be fully equivalent to access at ground level. This entailed a four-hour fire separation between these levels, and provision of firefighting facilities (particularly hydrants) to ensure that firefighters at Level 1 would be able to treat the fire as if they were approaching it from ground level. This was provided.

Within the Terminal itself, FSD's pragmatic requirement for a 28 000m³ volume limit for operational areas was achieved primarily through drencher water curtains and fire shutters. Drencher curtains are inevitably extremely hazardous to HACTL's automated systems and sensing equipment; a small fire setting off drencher curtains to a particular compartment could be potentially far more damaging through water than from the fire itself. To counter this, FSD eventually accepted that drencher operation could only be activated by a confirmation of both a heat and smoke detector.

Other FSD issues included provision of smoke extract systems for all occupied areas of the Terminal as well as the BSSs, where FSD were insistent that for political rather than practical reasons firefighters had to be seen to be actively involved, despite the provision of proven in-rack sprinkler systems. For the CSSs and CSS roadways (and for the Express Centre generally), FSD were satisfied that passive ventilation / smoke extract systems were acceptable.

12 fireman's lifts and staircases (with staircase pressurisation) provide firefighting access to all areas in the Terminal, but in view of the Express Centre's relative size and low overall height, it required only one fireman's lift and staircase (without staircase pressurisation).



16. Part of roof garden.

17 below. Rooftop swimming pool.



Mechanical systems

General

On all levels, air-conditioning / ventilation systems ducts were incorporated into the structural design. Below this structural and air-handling systems zone, the design team introduced the concept (successfully deployed earlier on the Toyota Plant in the UK) of providing two 500mm deep spacial zones for primary and secondary M&E distribution systems.

Later, Arup engineers in London and Hong Kong developed with the architects a planning grid principle in all operational areas that split the building in plan into a series of north-south and east-west running zones. Zones were allocated exclusively to one service - electric traywork, pipework, light fittings, etc. Also a horizontal planning grid was established with all east/west running services installed in the lower spatial zone or within the structural zone and all north/south running services in the higher zone.

Adopting these principles ensured that services clashes during construction were effectively non-existent and the final appearance of all services looks planned, organised, and neat. In office areas, services and structure were again integrated, with all main chiller water pipework, fresh air ductwork, and sprinkler pipework running through cast-in holes and slots in the structural beams. The main services distribution routes to both the offices and

operations areas are through two 260m long north/south running service tunnels, each 9m wide x 3m high, located in the basement with 11 vertical services cores directly on top of each basement corridor.

This building presented a myriad of space types to challenge the M&E engineers - from designing services for a snake examination and livestock room at one end of the spectrum to a karaoke room at the other! In addition there are forklift vehicle battery charging rooms, computer suites, the sports centre, and the kitchen, canteen, and restaurant.

The Express Centre was simpler in terms of M&E installations, with minimal air-conditioned spaces and electrically-driven cargo-handling systems. The building is open along both sides on Levels 0 and 1, the client requirement for an open-plan layout helping to ensure that 90% of it could be naturally ventilated. No smoke extract systems or staircase pressurisation systems were required. The services installation is fully integrated into the structure and architecture, with curved sprinkler pipework in slots cast in the roof structure and warehouse-type luminaires flush-mounted in cast-in openings in the roof structure.

Mechanical services

Cost benefit analyses determined that seawater cooling and electrical heating provided the best capital / running cost balance for the client. The building is cooled using five 3.4MW centrifugal seawater-cooled chillers to offset the effects of Hong Kong's high temperatures and humidity. Chilled water is distributed by three variable-speed pumping systems to all office areas at the north and south end of the building and Levels 3 and 4 of the operations area. Office areas are cooled by ceiling void mounted fan coil units connected to perimeter slot diffuser units and internal louvre face diffusers, and the operations areas by small AHUs between beams located 'within' the structure. Elsewhere, large central AHUs with return air fans are used. Fresh air comes via roof-mounted supply units, with heating provided to most of them to offset the 7°C outside winter air temperature. In addition perimeter fan coils in office areas are fitted with heaters. Cooling in computer suites is by floor-mounted, fine-control computer room units with humidity control.

The building also contains three large industrial refrigeration centres (cold room and freezers), the concept and scheme design for which was developed by Arup engineers with the client. Each refrigeration centre has its own refrigeration plant-room and heat reflection plantroom. Screw-type compressors provide cooling with water-cooled condensers, the condenser water being circulated to the building perimeter where it is cooled by fan-cooled radiators. Each refrigeration centre is subdivided into six or seven chillers and freezers, and has an original unique feature whereby some rooms can operate either as a chiller or freezer - done by flicking a single switch in the refrigeration plantroom. Also, all refrigeration rooms are monitored and controlled via the building management system (BMS) where amongst many features, room temperature set points can be adjusted and individual rooms shut down. In general, chiller room temperature is 1°C and freezers are -18°C.

A combined normal and smoke ventilation system is provided in the operations area. Statutory regulations require duty and standby fans, so for normal ventilation it was decided to run both fans at low speed, reducing noise and machine wear and extending fan and water life. In smoke mode only one fan operates, at high speed. In total 68 fans were installed with average capacity of 30m³/sec.

There is also a specialised truck exhaust fume extract system. Because trucks have to drive into the heart of the building, potentially dangerous gas concentrations must be kept below the maximum allowable safety levels, and to minimize inadvertent actuation of smoke detectors by vehicle exhaust in the truck dock areas. The system comprises a low-level extract duct and grills built into the structure, effectively removing the fumes at source as trucks reverse to unload or load goods.

The Express Centre has simpler ventilation and air-conditioning systems, again with seawater-cooled chillers. Three 625kW units are provided. Fan coils cool the small core office areas, and chilled water is provided to oil coolers on the two enormous dolly train lifts.

The fire services systems for both buildings comprise sprinkler, drencher, hydrant / hose reel, CO₂ gas flooding, and street hydrant systems inside and outside. The sprinkler system is a 1200m³ storage tank with eight pumps (duty and standby) serving both the Terminal and Express Centre. The sprinkler classification varied from Ordinary Hazard (OH) category II in office areas to High Hazard (HH) category III in the BSSs. Because of the amount and size of in-rack sprinkler protection needed and the overall size of the building, some 80 000 sprinkler heads are installed. The drencher tank is 550m³ capacity with five pumps serving both buildings, the system being designed to supply the largest compartment for 30 minutes.

There are also dry pipe systems in computer suites. CO₂ systems are installed in dangerous goods stores and battery charging rooms. During the FSD's inspection a real drencher test had to be carried out, and a 'dry (anything but!) run' was carried out a few days before the inspection to ensure no problems on the big day.

Plumbing and drainage systems in both buildings serve the many shower, toilet, and cleaning facilities. There is also a rainwater recapture system which includes a large tank and pumping system in the basement. The captured rainwater is used to irrigate the large planter areas on the roof.

One significant and not particularly surprising aspect of air cargo terminal operations is the huge amount of waste packaging generated, particularly timber pallets. Previously, subcontractors removed most of this, generally to landfill sites, but HACTL's heightened environmental awareness led to the provision of a purpose-built refuse treatment facility in the basement, converting timber pallets into woodchip, suitable for newsprint, chipboard production, or agricultural requirements.

Electrical installation

China Light and Power provide a double-ended supply to the site. Eight substations feed the Terminal and one the Express Centre, through 27 1.5MVA transformers with 40.5MVA of electrical power. Approximately 50% of connected power is dedicated to cargo-handling. For fire or other major emergency, three standby generators are provided with a capacity of 4.5MVA. In addition, HACTL are provided with independent UPS systems for their primary and secondary computer control rooms in the north and south offices respectively.

Early on, copper bus duct was chosen instead of higher voltage distribution via cables with provision of localised transformer stations, primarily on grounds of initial capital savings.

Inevitably, a building of this scale and operational diversity has a vast range of lighting systems. Lighting design expertise from Arup R&D was invaluable in establishing a framework for selecting suitable systems and units for all the external areas and a some within the building. Arup's proposal to use high frequency fluorescent tubes in the

offices (to improve one particular aspect of that environment) was, however, not accepted by the client. Much time was spent on the operational floors' lighting systems to find the most efficient and architecturally acceptable solution. Initially eight different systems were considered and tested, but this was relatively quickly reduced to two, based on four 250W units per bay in lieu of the client's preferred two 500W units. The final solution was the GEC *Lowmount 400* luminaire with a 250W fitting.

The Terminal has 14 passenger lifts, 12 firefighting lifts, five cargo lifts and two escalators (in addition to 34 automated cargo hoists), whilst the Express Centre has four passenger / cargo lifts and the two large dolly train lifts. The design of the latter, with their full 22 tonne load, was a project in itself.

Finally, and perhaps most important, are the BMS / AFA (automatic fire alarm) / SAC (security alarm control) group of systems. The BMS is easy to comprehend, but not easy to effect. AFA is statutorily essential, and critical to gaining a temporary occupation permit (TOP).

SAC, however, was a much greyer area. Security for HACTL is a key issue; statutory requirements insist on clear egress from any point of the building, but HACTL - dealing essentially with high value cargo - must restrict unauthorised access to many areas and preclude egress of small but dutiable or illegal items. This is achieved by massive CCTV networks and AFA interlocked systems, allowing free escape in fire but minimising illegal infiltration. In the early stages it was decided that BMS / AFA / SAC would be let as one subcontract (to Honeywell), as they were closely interdependent.

Testing and commissioning the M&E systems was an enormous task. The main building contractor appeared either unwilling or unable to offer this overall service, and after prolonged negotiation with the client it was finally agreed that Arup would additionally test and commission, and a team of engineers came to Hong Kong. For a building as apparently (initially) simple, an experienced team of testing / commissioning engineers was essential. The team provided both a management and a hands-on role and was assisted by all the services subcontractors' teams.

Reference

(1) DILLEY, Philip and GUTHRIE, Alistair. Kansai Airport Terminal Building. *The Arup Journal*, 3(1), pp14-23, Spring 1995.

Credits

Client and project managers:
Hong Kong Air Cargo Terminals Ltd

Lead consultant, engineering design, building project management, supervision and testing/commissioning:
Ove Arup & Partners

Architectural consultant:
Foster and Partners

FSD consultants:
Loss Prevention Council

Quantity surveyors:
Levett & Bailey

Main building contractor:
Gammon-Paul Y JV

Cargo handling systems contractors:
Mannesmann Demag Fordertechnik
Murata Machinery Ltd

Piling contractor:
Vibro/B+B Construction

Key architectural subcontractors:
Josef Gartner (vertical cladding)
Seele (roof steelwork and cladding)

Key M&E subcontractors:
Honeywell (BMS/AFA/SAC systems)
Schindler (lifts/escalators)
Young-Drake & Scull (electrical/MVAC installation)

Illustrations:

- 1: Mike Harley
- 2: Foster and Partners
- 3, 4: Jennifer Gunn/Sean McDermott
- 5: Ove Arup & Partners
- 6-18: Colin Wade

18.
The Terminal at sunset.



The Lufthansa Catering Facility

Henry Arundel
Kieran Flynn
Paul Suett



Introduction

LSG Lufthansa Sky Chefs is the largest airline caterer in the world, with over 100 facilities across most of the world's major airports. They had operated at Kai Tak alongside Cathay Pacific Catering for over 15 years, and were eager to carry on and expand their customer base at the new airport. With the initial annual passenger throughput of 35M rising ultimately to 87M, Lufthansa's new unit had to be considerably larger than its predecessor, and capable of future expansion.

Flight kitchens are complex facilities. Lufthansa's customer base of 25 airlines included such giants as British Airways, JAL and Virgin, each with its own style and menus. Catering units not only have to look after the provision of food, but also all the other items one finds on an aircraft including blankets, cutlery, and duty-free goods.

Not surprisingly they need large separate storage areas for each airline as well as bonded stores and customs facilities.

The major ownership of LSG Sky Chefs rests with Lufthansa, Dragonair, and CITIC - mainland China's primary investment vehicle in Hong Kong. CITIC owns 35% of Lufthansa Catering in Hong Kong, and were eager to see their new investment in good hands. Arup's project management group in Hong Kong were already acting as owner's representative on several CITIC projects, and were asked in October 1995 to submit an outline proposal for the catering facility.

By then, however, Lufthansa had already engaged their own project manager to negotiate with the Airport Authority on the franchise agreement - and he had also begun negotiations with Leighton Contractors Asia, one of Hong Kong's largest, for a design-and-build (D&B) contract. Arup discussed with Lufthansa's project manager supplementary services they could provide, beginning by challenging the decision to negotiate with only one D&B contractor. Lufthansa's project manager explained that the bid was unsolicited and included a GMP (guaranteed maximum price), which Lufthansa's main board favoured.

With this basic contract strategy already in place, Arup suggested they review the contractor's offer, pricing, and programme. With a little over two years until airport opening, it was too late to consider reverting to the traditional procurement strategy of design, competitive tender, and construction. One complication was that Lufthansa's own unit in Frankfurt were designing the kitchens, and time constraints made then unable to supply sufficient detail for architects and engineers.

Time was short and Arup started work as owner's representative. The commission was to expand.

The Arup team

The commission needed both project management and building services skills. Arup's project manager came from the latter discipline because of the complex systems needed to service the specialist catering equipment. He and his team concentrated on design checking the building services designs from the contractor's designers, as well as writing the specifications for the catering equipment sub-contracts for LSG. He also chaired monthly progress meetings with LSG and the contractor.

Design checking of civil and structural elements was undertaken by Arup structural engineers, whilst their HK project management group - with back-up from the Birmingham office - checked and agreed franchisee changes with the contractors, and processed monthly payment certificates.

Contract negotiations

The D&B contract had to incorporate back-to-back requirements built into Lufthansa's franchise agreement with the AA. For this reason, Lufthansa decided to use their corporate lawyer to draft a bespoke contract rather than select and modify one of the standard forms used in Europe for D&B. It basically comprised three sets of documents.

The first was the contract conditions drafted by the lawyers, the second the 'Employer's Requirements':

- a general description of how the catering unit was intended to work, including work flows, numbers of meals per day, working shifts, etc
- diagrams for each floor showing the layout of functional areas, ie how the hot kitchen related to the tray set area, etc
- a schedule of kitchen equipment, plus utility requirements for gas, water, drainage, and electricity.

The contractor responded to these basic requirements with Contractor's Proposals as follows:

- a set of 1:100 layouts based on the employers functional diagrams
- a cost plan with GMP
- a programme and milestone schedule
- a specification.

Under the D&B contract, the contractor was responsible for designing the entire facility save for specialist equipment from Lufthansa's Frankfurt design unit including the high bay store, general kitchen equipment, dishwashers, cold rooms and freezers, vacuum waste system, bakery, and commercial laundry. Arup identified this division of design responsibility as a potential risk area early on, and attempted to cover it by insisting that they be nominated sub-contracts to the D&B contractor, thus putting co-ordination responsibilities with him.

1. The new facility at CLK.

After a series of negotiations on price and programme a contract was signed in March 1996, leaving a little over two years to completion. The contract was based on a GMP of HK\$440M with a 70/30 bonus provision for the client / contractor on agreed cost savings.

Design checking

One of the AA's conditions in granting Lufthansa the franchise was that there should be an independent checker to warrant that the design was undertaken professionally and according to the AA's own general specifications. Arup was initially required to check that the design was 'in accordance with the contract' and 'was found to be satisfactory', but it soon became necessary to clarify exactly what this meant, and the contract wording was modified.

Arup's design checking - in stages based on packages of information submitted by the D&B contractors - commenced in March 1996 and was completed in March 1998 when certificates were issued. Three separate checks were undertaken: mechanical and electrical, structural, and architectural, the latter by the small architectural practice PTA.

The M&E design check was divided into scheme and detailed design phase, the former including a review of all design criteria (light levels, room temperatures, noise levels, duct velocities, etc). Arup also looked at systems proposed by the contractor, questioning for example the use of air-cooled rather than seawater-cooled chillers for the air-conditioning, the level of standby facilities, and types of lighting. The detailed design check was of calculations submitted by the contractor, with spot checks for cooling loads, lighting levels, plumbing and drainage. In addition Arup checked that all fire services met or exceeded statutory requirements. All this proved a valuable exercise for the client as it identified deficiencies in the design (though none serious) and led to more cost-effective and energy-efficient M&E systems. An example was using the rejected heat from the food storage chillers and freezers' refrigeration plant to preheat the cold water feed to the kitchen hot water calorifier system.

The structural design check embraced all structural calculations and drawings to ensure the design was both adequate and safe. Many meetings were held with the contractor's designers to ensure both that Arup understood their design philosophy and that they understood the modifications required in their design as a result of the checking. Again, areas in the design proved to need modification, eg pile caps needed extra reinforcement in some areas and less in others.

The architectural design check comprised a review of the building for statutory requirements - escape distances, locations of hoses, fire rating of partitions or doors - as well as for durability and waterproofing. This check also covered the roof drainage system.

Soon after the contract was signed on 7 March 1996 LSG asked Arup to help prepare the tender documents for various specialist equipment packages. These were all performance-based documents, the detail design being the responsibility of the appointed subcontractor. In essence the client provided the equipment design criteria, equipment schedules, and preliminary layout, with Arup adding general requirements, materials and workmanship, and testing and commissioning specifications. Arup was also involved in tender review, tender interviews, and recommendation of award. The list of tenderers was truly international, with suppliers from Norway, Portugal, Germany, Switzerland, Japan, America, and the UK. The subcontracts were awarded in the second half of 1996 and early 1997.

Of the seven specialist equipment packages, the four major ones were:

Chillers and freezers:

1600m² of units for perishable goods storage
The system comprised central refrigeration and heat rejection plant for chiller systems (2°C) and a parallel plant for freezer (-20°C), embracing the first usage in Hong Kong of the refrigerant R134A for such purposes. In addition the heat rejection plant was fitted with a refrigerant-to-water heat exchanger to recover heat and use it to preheat the kitchen hot water system.

High Bay Store:

an automated racking storage system
50m long, 25m high, and 13m wide, this can store 2400 loaded pallets weighing up to 1000kg each. It houses a wide range of food product and airline accessory equipment, including canned fruit and vegetables, alcohol, cutlery, and blankets, and is air-conditioned with the temperature 9m above floor level kept at 20°C for storing more temperature-sensitive foods. The system operates by barcode; as soon as the barcode on a pallet is read the computer control system memorises it and allocates a position in the store - remembering the position, of course, for future retrieval. The barcode contains much information including date of entry and expiry date of product. If the same requested product is stored on more than one pallet, the computer will automatically select the pallet with the earliest expiry date.

Kitchen equipment

This comprises some 300 items with M&E services connections, including automatic vegetable peelers, gas-fired wok burners, automatic meat tenderisers etc.

Dishwashing equipment

The five assembly line types of washing machine comprise one glass washing line, one bulkware working line (for large items of cookware), three tray, cutlery, and dishwashing lines, and one cart washing machine - the carts we have all seen wheeled up and down aeroplane aisles are put through an automatic 12m long washing machine. All machines have hot water rinse and dryers, so all items are dry on exit from each machine.

Cost auditing

The D&B contract included a mechanism for quickly agreeing changes to the scope of the works. If the client wanted to change or add a piece of equipment he raised a 'Franchisee's Change'. The contractor then had to respond within a week with the time and cost implications and, if agreement was reached, the change was authorised. Other clauses dealt with contractor-requested changes to quality or materials, with a 70/30 saving mechanism for client / contractor should the cost of the works come below the GMP. This principle - fine in theory - relied on not too many changes being authorised. Arup had to check the pricing of the changes and advise Lufthansa accordingly.

Site representative

Arup's biggest concern with the D&B contract was site quality control. The D&B contractor had his own site inspection team and the contractor's designers also undertook to make periodic visits to check quality, as in a traditional contract. Arup's site representative's primary duty was thus not quality checking and approval on site, but rather to ensure that the equipment LSG selected in the sub-contracts was as specified.

He also liaised between the contractor and LSG over any site-related queries. His other main responsibility was to receive instructions on behalf of LSG from the AA, and then formally transmit them to the contractor.

Arup's site representative monitored progress on site and transmitted information to the project manager for incorporation in the monthly progress report. Later, he was involved in signing off acceptance tests for specialist equipment and defects inspections.

2 below:
The High Bay Store.



Decommissioning the Kai Tak facility

Decommissioning and planning the move to Chek Lap Kok began in summer 1996, with Arup commissioned to start the process with LSG's Project Director. The first task was to contact the Lands Department to ascertain the status of the lease conditions. No answers were forthcoming, so an initial budget was calculated on the worst scenario, including for demolition of the existing facility (lease conditions), staff training and relocation costs, and the cost of the relocation itself.

In late spring 1997 the move committee was formed between the operational heads of LSG and other relevant parties like Customer Services as well as an Arup representative. Initially, the committee looked at the broad aspects of staff training and familiarisation, recruitment, identification of new equipment required, estimates of volume to be moved, and issues relating to operational readiness (OR) requirements.

The AA held the first meeting on OR and the move in summer 1997. Initial plans were drawn up to reflect first estimates of volumes to be moved and how - by land, sea, or air. Sea was deemed too slow, and unnecessary as its domain was largely for large bulky objects. Air was a viable alternative to land: one of LSG's clients could fly the facilities contents to CLK from Kai Tak as part of their overnight placing. However, flexibility was crucial - the planes' timetable was unlikely to coincide with LSG's window (much larger) and the state of airside access at CLK was unknown.

Thus road transport by land was chosen.

In early summer 1997 several removal companies were contacted. Four were short-listed and tenders issued in October 1997.

The award went to BALtrans International in December 1997, and the contract was specific about how the facility could be moved. Restricted working hours were dictated (packing after 17.30 and loading containers after 23.30 only), and reimbursement based on a rate per m³.

By now the new facility was near completion, and commissioning programmes were formed to enable LSG staff to plan staff training and familiarisation trips. These began in early 1998, with training from May 1998 once the final opening date at CLK had been confirmed.

The OR programme also embraced the run-up to full production at CLK and the necessary run-down and decommissioning of Kai Tak. This was integrated with the commissioning programme and allowed for items like planning the pest control and hygienic cleaning of CLK, as well as showing LSG when they would take over the facility from the contractor, and thus allow for this in their staffing plan.

In parallel, the on-going meetings with the AA about the move itself became more frequent and detailed. The first move plan, produced by the AA for the benefit of the business partners in May 1998, detailed move times for each vehicle from each participant, plus details of the proposed routes to CLK, and information relating to permits and licenses required for all. In the same month, the LSG move plan was issued by BALtrans.

This took the AA plan one step further with specifics for each LSG department, strategising lift usage and identifying the windows during the operational day that movements could be made. Within the plan contingencies were also detailed that allowed for delay of CLK opening, red and black rainstorms, and typhoons.



4. The Kai Tak facility being closed down on the night of the move.

By now a regular removal committee had been formed, comprising representatives of BALtrans, Arup, and LSG, to agree on the fine detail of the move.

This made BALtrans entirely familiar both with LSG operating practices and the building itself. Initial 1997 estimates had assumed around 250 6.1m containers-worth of equipment requiring to be moved, but further surveys by BALtrans showed this to be slightly high and the plan was reduced to 220 6.1m or 110 12.2m containers.

An initial night trial, carried out on 5 May using one container and loading from the third floor equipment store, showed lift availability and reliability to be crucial to the move's success. A second, daytime, trial one week later using two containers was much better; the one-hour loading target was achieved with no disruption to operations. This proved the practicality of daytime removal operations, and two time slots at 10.30am and 3.00pm were identified.

In late May and early June all stock from a warehouse at Yau Tong was moved to CLK to coincide with the High Bay Store start-up. This was a perfect proving-ground for the new system; by the airport opening most problems had been solved.

The first major move, over the 21 June weekend, was the administrative offices. Friday night was occupied with packing, and Saturday with the move itself (five containers and three lorries). On Sunday the desking was assembled and LSG staff unpacked their belongings.

By the week before the main move, 43 12.2m containers had taken a variety of operational and office equipment to CLK. This was c40% of the total, and by the end of the final week 18 more 12.2m containers had gone.

This left just under 50% of the equipment to be transported on the Sunday night and in the week thereafter.

25 containers were planned for the Sunday move, each with its own time slot and planned contents. Planning the Sunday move was concentrated and dictated by Kai Tak's Arrivals schedule. Dishwashing was planned to stop after the 1.30 flight had come through, giving the team time to get to CLK before the first of the arriving dirty carts followed them across - in containers or LSG hi-lifters, whichever were available. By doing this, the facility could be closed earlier rather than wait for all flights to be washed and then transported. As flights arrived, they were loaded directly onto the containers, on the ground floor if possible, or stored temporarily on the first floor and moved down using lifts or any spare hi-lifter.

By 1.15am Monday the last container and hi-lifter had left. A total of 32 containers had been loaded since 12.00 noon Sunday, averaging 20 minutes a container. The last hi-lifter arrived at 2.15am Monday on the back of a breakdown truck, having ground to an unplanned halt just outside CLK.

Following the night move, nine more containers and seven frozen food trucks finally cleared the last of Kai Tak. The building was decommissioned by 22 July 1998, not quite two years from the first stages of planning to final shutdown.

Total containers moved	105
Total trucks	3
Total LSG trucks	22
Total cars/vans	13
Volume moved	3795m ³
Staff on the night:	16 BALtrans in Kai Tak, 25 at CLK, plus various LSG management.



3. The move, 5 July 1998.



Credits

Client:
Lufthansa Sky Chefs
Project manager and checking engineer:
Ove Arup & Partners
Moving contractor:
BALtrans International
Illustrations:
1, 5: Colin Wade
2: Gareth Jones
3, 4: Damon Yuen

5. Inside the new facility.

Ground Transportation Centre

John Burrows Alice Chow
Naeem Hussain Martin Kirk
Ian Taylor Graham Thomas

Introduction

The Ground Transportation Centre (GTC) is the land transport focal point of the new Airport. It is a multi-modal interchange, fully linked with the Terminal Building, incorporating road, rail, bus, and taxi connections to Hong Kong and The New Territories. At the centre of the GTC is the Airport Railway Station, which links to the Terminal's Arrivals and Departures levels via air-conditioned bridges; around and within this building occur the interchanges between all the different modes of transport, whilst the remainder of the site is covered by network of road and rail links, long lengths of which are on viaducts.

In October 1993, the Airport Authority (AA) appointed Arup as prime agent for the concept and preliminary design of the GTC and approach roads, and a year later the firm was commissioned to complete the detailed design. Construction of the foundations and basements began in early 1995, with the principal civil and building contracts following in November 1995. The GTC was opened with the rest of the airport on 6 July 1998.

Arup led a design team comprising two architects, Foster and Partners and Anthony Ng Architects Ltd, Parsons Brinckerhoff (Asia) for the mechanical and electrical works, Davis Langdon & Seah Ltd, as quantity surveyors, and Urbis Travers Morgan as landscape consultant. This was a multi-disciplinary project involving the skills of many parts of Arup, including building engineering, bridge engineering, highway and railway engineering, acoustics, fire engineering, maritime, and geotechnics. It was also an international effort with design work carried out in or staff seconded from offices in Coventry, London, Cardiff, Leeds, Cambridge, Sydney, Brisbane, the Philippines, and of course Hong Kong.

Concept and preliminary design

The original airport master plan proposed a station within the Terminal Building envelope, but an early action by the PAA removed it to form a separate transport interchange. As a result, the GTC will be able equally to serve a second terminal building in the future.

The primary objective of the GTC's road system was that it should still be free-flowing under the predicted maximum demand for 2010, with expansion capability to 2040. The system grade-separates principal traffic movements and allows vehicles to recirculate between major car parks, drop-off kerbs, and other facilities.



1. The main architectural feature is the large atrium spanning over the pedestrian routes and joining the two rail platforms and Terminal access bridges.

In concept, the GTC building comprises five levels. In the lowest are three underground structures:

- a basement for processing baggage checked in at Hong Kong or Kowloon, linked to the Terminal Building by a tunnel
- a tunnel and maintenance facility for the advanced people mover (APM) system running under the GTC and out to the aircraft gates
- another tunnel allowing taxis to exit the GTC without conflicting with pedestrians.

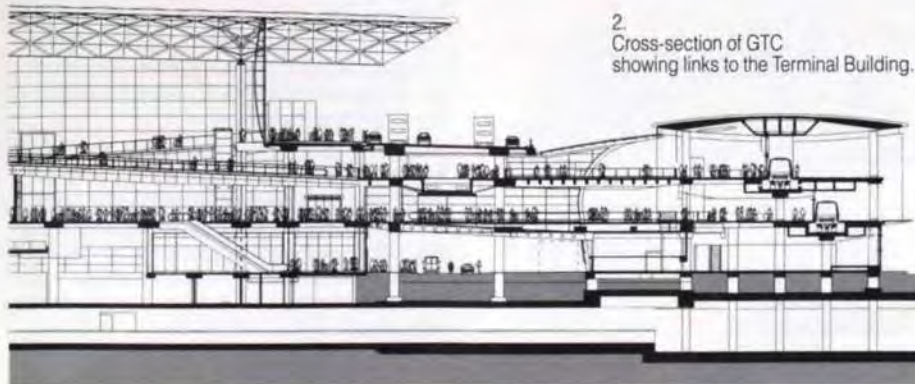
The ground level is occupied by road traffic, with separate, covered, pick-up areas for buses, coaches, hotel vehicles, and taxis. Private car pick-up facilities are provided in car parks at either end of the Terminal.

The second and third floor levels form the Arrivals and Departures platforms of the Airport Express Line (AEL). This key feature of the station allows free movement into the corresponding levels in the Terminal Building - without a change in level for Arrivals passengers.

This necessitated grade separation of the twin rail tracks entering and leaving the GTC, with long sections of viaducts.

At the highest level, Departures road traffic is carried adjacent to the Terminal by a long structure with several layers encompassing a transitional level for rail passengers and bridge links to the station. A Departures forecourt and median strip provide 650m of kerb length along the Terminal façade. In plan, the GTC is configured with the station platforms in the centre of the building and 'back of house' functions accommodated at each end in 'bookends'. The principal pedestrian circulation is between the station and the Terminal.

The station is mainly a beam and slab concrete structure, its roof in exposed, cast in situ concrete enclosing large ducts for train and station ventilation. The 'bookends' are clad in lightweight metal panels. The main architectural feature is the large atrium spanning over the pedestrian routes and joining the two rail platforms and Terminal access bridges. This is some 230m long and is formed by curved vertical members spanning between the ground and the roof, with 2 x 3m glass panels. The GTC is finished to the same high standard as the Terminal, with granite, exposed concrete, and metal panel cladding predominating.



2. Cross-section of GTC showing links to the Terminal Building.



4 left: Model showing the differing cross-sections of the highway viaduct and railway viaduct.

The highway and railway viaducts are highly visible to passengers and a key feature of the overall site, so a family of bridge structures was devised that would be economic to build, visually appealing, and complement the architecture of the Terminal and the GTC. They are on varying curved alignments with a variety of lane configurations, which favoured in situ construction. The highway viaducts have post-tensioned concrete multi-cellular decks with a 'shallow-tub' cross-section, chosen because of its particular suitability for long curved spans with centrally located columns and its high torsional strength. Its slender appearance also reduces the apparent depth of the viaduct.

Its columns are in reinforced concrete, with flared tops; vertical ribs improve the concrete weathering characteristics and provide a contrasting texture to the smooth surface finish of the decks.

Due to their grade separation, the railway viaducts are single-track structures, with each track on a single cell post-tensioned concrete box, moulded with curved edges to complement the highway bridges and to follow the shape of the flared columns below, themselves derived from those of the highway viaducts. The parapet detailing was also a key feature, incorporating sloping sides with radiused corners.

The project included several other elements besides the station and viaducts. Once departing passengers have alighted, trains travel to a cleaning facility for litter removal before coming back via a crossover to collect arriving passengers. This facility is an at-grade concrete structure next to the airport island's sea wall, which had been designed to tolerate some overtopping during extreme conditions. Arup's London civil engineering group looked into how the railway could be shielded from this and as a result a concrete wall was built on top of the rock defences.

Finally, several airport support function buildings were included.

As the airport design progressed, the AA became aware of the opportunities for office development near the Terminal. After completing the preliminary design, the team was instructed to prepare a revised concept study incorporating 60 000m² of offices into the GTC area.

The study - with offices over the GTC - was presented with acclaim to the AA in December 1994 but unfortunately the development could not be financially justified, particularly within the increasingly tight construction programme, and the AA's initiative was not rewarded.

Station detailed design

Although the preliminary station design and detailed design of the basements and foundations was prepared in Hong Kong, the detailed design of the station superstructure was carried out by Arup in London. With trains at the second and third levels of the structure, high loads had to be accommodated, so the structure was heavily reinforced.

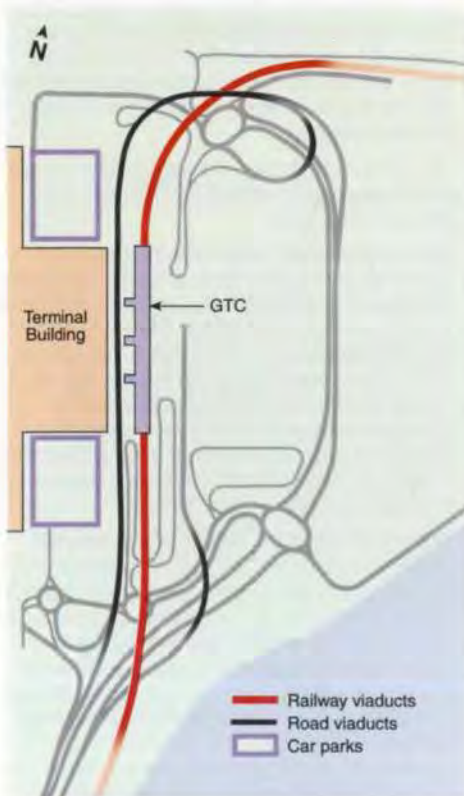
The trains also complicate the acoustic and life safety design of the station. With the large open atrium joining the major public spaces together, and with noise - particularly structure-borne - from the trains playing a major role, much judgement was required beyond traditional analysis methods. As in many similar facilities, the vast areas of hard finishes complicated the acoustic performance of the public spaces and Arup Acoustics worked closely with the architect to ensure that intelligibility was maintained.

Roads and railway detailed design

The preliminary design and design co-ordination for the roads and railways was undertaken in Hong Kong, and the detailed design in Coventry. The complexity of the GTC approach roads - grade-separated and with tight geometry - was a considerable challenge. They were designed and modelled using InRoads software compatible with the Arup system and the AA's Microstation-based CADD system, three-dimensional modelling of these elements being essential to determine clearances accurately and to optimise the alignments.

The constraints of the terminal interfaces and the configuration of the roads and railways resulted in parts of the road system being below the ultimate high water levels of the island. These areas were considered liable to flood in extreme conditions and, to prevent such events closing the airport, two solutions were adopted.

In one area the roads are founded on permeable fill and water infiltration could occur from below, so here a concrete liner was constructed under the roads extending to the highest anticipated water level. Other roads are founded on Chek Lap Kok's original bedrock, through which seepage could pass via fractures caused by the blasting. In these areas pressure grouting was used to limit flows,



5. The GTC and associated Arup-designed infrastructure.



Viaducts detailed design

The detailed design of the highway and railway viaducts was carried out in Arup's Coventry and London offices respectively.

Highway viaducts

The design comprised the following structures:

- Terminal 1 approach ramp: seven spans, total length 264m, maximum span 42m
- Terminal 1 exit ramp: 10 spans, total length 408m, maximum span 45m
- South expressway bridge: six spans, total length 183m, maximum span 37.5m
- North expressway bridge: three spans, total length 70m, maximum span 29m.

Although following a family theme, each has its own characteristics of highway geometry, articulation, construction staging, and foundations.

The approach ramps and expressway bridges were designed as continuous structures with no intermediate joints, whilst the longer exit ramp has two fixed columns near the middle to provide articulation; expansion joints at each end cater for up to 53mm of thermal movement.

The superstructures were designed using in-house software programs BRILLO (Bridge Loading) and PREPAK (Prestress Package).

The shallow sloping soffit walls of the decks allowed for simple two-stage construction of the section without top shutters. The cross-section, although seemingly simple, led to some difficult geometrical problems due to varying superelevation. Keeping constant dimensions for the main 'shallow-tub' section and varying the geometry of the curved parapet beam solved the problem. Accordingly all the formwork for the deck sections is kept as uniform as possible.

The substructures were relatively straightforward, although some columns are large. The column outline for the ramps has a 2m x 2m cross-section at the base to deal with large vertical reactions and cantilever bending due to horizontal loads.

About half the substructure footings are founded into the bedrock of the original island. However, to the north end of the site, bedrock dips sharply away and foundations are provided by large diameter bored piles.

Railway viaducts

These were in many ways a variation of the Tsing Yi design (see pp38-43), with a total length of around 1.8km. The decks consist of prestressed concrete boxes with internal cables coupled at the construction joints. Crucial to the design of a railway viaduct is the decision on the size and number of rail expansion joints. A spacing of about 100m, coinciding with the viaduct expansion joints, was used.

The deck was constructed by the span-by-span technique which minimised the amount of falsework and formwork and maximised their re-use. As at the Tsing Yi viaduct, in some cases the deck construction progressed towards a pier already supporting an adjacent pier. A special end diaphragm was used which allowed the cable anchorages to be placed further inboard of the box so as to permit stressing.

Conclusion

The Ground Transportation Centre of the New Hong Kong Airport was an interesting and exciting project, utilising the best of Arup's skills in international, multi-disciplinary working. Arup was prime agent for the GTC concept and co-ordinated a team of engineers and architects throughout its design and construction. Despite a very aggressive programme for both design and construction, the project was successfully completed for the opening of the airport in July 1998.

Credits

- Clients:*
Airport Authority Hong Kong/MTRC
- Lead consultant and engineering design:*
Ove Arup & Partners
- Architects:*
Foster and Partners
Anthony Ng Architects Ltd.
- Mechanical & electrical engineers:*
Parsons Brinckerhoff Asia Ltd
- Main contractor:*
Nishimatsu Construction Co. Ltd.
- Quantity surveyors:*
Davis Langdon & Seah Ltd.
- Landscape designers:*
Urbis Travers Morgan Ltd.
- Illustrations:*
1, 3: Colin Wade
2, 4: Foster and Partners
5: Jennifer Gunn
6: Gareth Jones

6.
Platform for Airport Express trains arriving from Hong Kong.



Challenges

As with any large multi-disciplinary project, the challenges faced by the design team were both organisational and technical.

Organisational challenges

Not the least challenge in forging a fully integrated team was to establish clear roles for the two architects. Arup tried to foster the feeling of a single architectural team by setting up an architectural office within the engineering office, staffed by personnel from both practices. Although this worked reasonably well, it did require considerable management input by Arup.

One of the responsibilities of Arup's Hong Kong team was to co-ordinate the work carried out in seven remote offices - a complicated task requiring understanding and patience from all.

Further complication came from the GTC's interfaces with other major design contracts. This being a brand new airport, inevitably the AA continually developed its ideas on how it would operate, which in turn led to design changes.

To control this process, Arup implemented a system of written orders for changes developed as part of the Quality Assurance system. This worked well, despite some differences of opinion over the significance of particular client change orders.

The AA awarded the construction contracts, Arup's responsibility being limited to the supply of documents for tender. The first contract, for the substructure, was delivered a mere six weeks after the firm was appointed to carry out the detailed design. At this time the office concept was in preparation, putting severe pressure on the designers. Nevertheless the contract was awarded and work started on site in early 1995. In April 1995, three and a half months after the final preliminary design was completed, tender documents for the superstructure and road/viaduct contract were issued to the AA. However, funding discussions between Britain and China were then at an advanced and delicate stage, leading to a period of delay. As a result the contract was not let until late 1995, with completion originally scheduled for March 1997.

Arup's site involvement was originally limited to a visiting role, site supervision being the responsibility of the AA. However, a resident engineer was requested for the substructure contract, to assist in supervision. As a result of experience gained on this contract and on the Terminal, Arup provided a resident team on site, under AA supervision, to assist in the remaining contracts.

Thus, the design of modifications was split between three offices: architectural and engineering work was carried out on site, except where extensive changes were required - these were undertaken either in Arup's Hong Kong office or the UK office responsible for the original work.

A final challenge was the double-headed nature of the client. Although the Mass Transit Railway Corporation (MTRC) had entrusted its railway works to the AA, it still played an active role in the project's design and execution.

The inevitable differing priorities, coupled with the aggressive programme, caused additional difficulties.

Technical challenges

Each discipline had its own challenges, but some aspects of the GTC created difficulties for all. The MTRC is well used to designing stations in mixed-use developments. However, these are normally developments with private owners. The airport was different, with both the terminal and the GTC being public transportation facilities and dependent on each other for operation.

Both organisations had their own policies for security, life safety and building systems, their own specifications, and their own identities to promote in the GTC. As a result the MTRC and AA areas of the building are discrete in many ways - with separate public address systems for instance - despite being physically interwoven.

Fire engineering: the Terminal Building and the MTRC stations

Peter Bressington

The approach

The commissions for the fire safety design of the Terminal Building at Chek Lap Kok and all the MTRC stations on the LAR gave Arup Fire two of their most interesting and challenging jobs. This was fire safety design on a grand scale, covering strategic advice on means of escape, compartmentation, fire fighting access, and developing criteria for fire system design. The objective was to provide a satisfactory level of fire safety without imposing restraints on the termini functions, to be sympathetic to architectural aspirations, and to achieve cost-effective design.

Providing a good, practical level of fire safety, without unnecessary restrictions on the way these termini are used, necessitated an understanding of how they function in terms of building environment and use by passengers and staff. Arup Fire had to study fire scenarios, fire load and distribution, and look at how thousands of people could be evacuated in the safest manner.

Transport terminal buildings, with potentially long escape routes in large volume spaces, demand an understanding of fire development and smoke spread to ensure people are able to move away from a fire. A fire engineering approach was used to determine the criteria for the fire safety design of the stations and Terminal Building. Essentially this brings flexibility, so that expenditure on fire safety measures in one area is used to offset reductions in another. Advantage was taken of the positive inherent features of the building design and use; a high ceiling removed the need for roof level smoke extraction. Early response detection and alarm systems offset longer travel distances.

The approach and equations used to establish the fire safety strategies were based on sound and internationally recognised research and statistics. Where appropriate, codes specifically addressing transport termini were consulted. For example, *NFPA 130* 'Fixed guideway transit systems'¹ was used to determine certain elements of fire safety design for train termini.

Arup Fire were also involved in a major way in establishing the parameters used as a design standard for general application on all the LAR stations. The involvement with MTRC and the Airport Authority included the development of design fires, computational fluid dynamic (CFD) analysis of station extract systems, and proving the 'Cabin Concept'² with full-scale fire tests.

Though Arup Fire began to develop the fire strategies in 1992, long and detailed negotiations with the authorities were involved, and Arup Fire was dealing with design issues right up to the opening of the Airport in 1998.



Evacuation

In developing the fire safety strategies, passenger termini numbers and movement of people were prime concerns, and the evacuation strategy for the Airport and LAR was generally based on the operators' projections for the busiest period. Account was taken of the expected population density and peaks of passenger movement, so the design of the termini reflected these and the way people would move in and around the space. Circulation space, stairs and escalators were designed on the basis of normal operating peak conditions. The emergency escape strategy makes full use of these normal exits and circulation routes, for example escalators, to allow escape to another level.

Evacuation was arranged so that people can escape in reasonable time and be protected from the immediate effects of fire and smoke as they make their way to safety.

The evacuation strategy was related to the occupancy characteristics of the building, so that when the strategy was developed, issues like passenger reaction to directive public address systems and the need to carry luggage were considered.

Hazard and risk

The various areas within the stations and Terminal Building were analysed so that the level of fire measures could be targeted to suit the level of hazard. The main areas of the public spaces in the termini have positive fire safety features. They have low average fire load, with hard surfaces that severely limit fire spread. This meant that Arup Fire were able to agree with the authorities that the very large compartments did not compromise fire safety for passengers or firefighters. However, there are locations where a higher level of fire load demanded special consideration and fire safety measures.

Back-of-house areas were treated in a fairly conventional way, with compartmentation and fire systems meeting Hong Kong's prescriptive code requirements.

1 top:
The great height of the in-town check-in hall at Hong Kong Station (see pp52-60) was a significant factor in the strategy for its fire protection.

Design fires

To calculate the various parameters relating to fire safety, it was necessary to establish a set of design fires for each of the areas.

These allowed design decisions on fire spread, compartmentation, and smoke extract requirements to be established. Arup Fire used existing data on growing fires for various fuel types, compartment fire growth, and development and sprinkler action. A baggage fire was used as the design fire in the public circulation areas, a sprinkler controlled fire for the retail areas, and a train fire for platforms on the LAR.

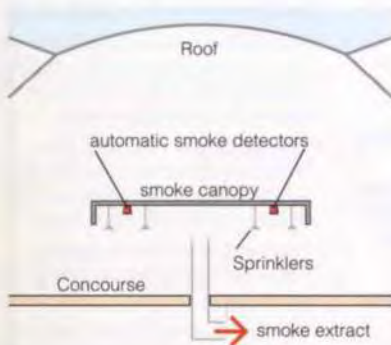
Fire systems

Within the Terminal Building, sprinklers were provided in the retail areas, back-of-house areas, and baggage hall. Because the main circulation spaces have a low fire load, sprinklers were not installed at the roof, its height above the lowest level rendering them ineffective due to response and water discharge characteristics. Smoke filling calculations confirmed that the very large area and height of the Terminal Building meant that smoke would not descend to a level to threaten passengers during the escape phase, so smoke extract

or smoke vents were not needed in the roof. Here was installed an early detection aspirating smoke detection system, whose network of discrete small pipes cannot be seen by those admiring the roof.

The fire strategy for the stations was similar to the approach for the Terminal Building. Fire measures were targeted to specific areas where there was a need to respond to a potentially large fire or where it was necessary to provide enhancements for means of escape and firefighting. Sprinklers were not installed in the concourse and platform areas due to the nature of the hazard and risk.

Smoke control systems were designed to stop smoke flowing from a fire area into an adjacent place of safe passage, and to provide a smoke-clear layer for the concourse and platform.



2. The Cabin Concept.

Within the Airport Terminal and the LAR stations, retail occupancies were recognised as requiring special consideration. Here the Cabin Concept was introduced to protect these higher fire load areas, stop fire spread, and prevent smoke from affecting escape and fire-fighting activities. This method compensates for the very large uncomparted areas in the designs.

The Cabin Concept isolates the fire within the affected area by controlling it with sprinklers and extracting smoke. To accomplish this a reservoir is formed by a downstand arranged around the area, its depth depending on ceiling height, extract rate, and design fire size. The remaining perimeter area can then be left open to the surrounding concourse. A combination of smoke extract, detection, and sprinklers provides the equivalent of conventional

compartmentation. The advantage of the Cabin Concept is that people in the affected retail area can move directly away from the fire, and fire-fighters can easily gain access to it.

Arup Fire were asked by Hong Kong Fire Services Department (FSD) to do a series of fire tests to verify that the Cabin Concept achieved the design criteria. This had to show that a combination of smoke detection, sprinkler protection, and smoke extraction can keep the space outside the test area substantially free of smoke, even in the event of a serious fire within the test area.

A specially constructed test cell was built at the Fire Services Training Ground, designed to represent a typical open retail area with downstands and fire safety measures as described above. Tests were carried out for both the Airport Authority and MTRC, and witnessed by the FSD, the Government Buildings Department, and the Railway Inspectorate.

These tests showed the effectiveness of the Cabin Concept in preventing smoke spreading from beyond the area of the origin of the fire.

Credits

Clients:
Airport Authority Hong Kong/MTRC

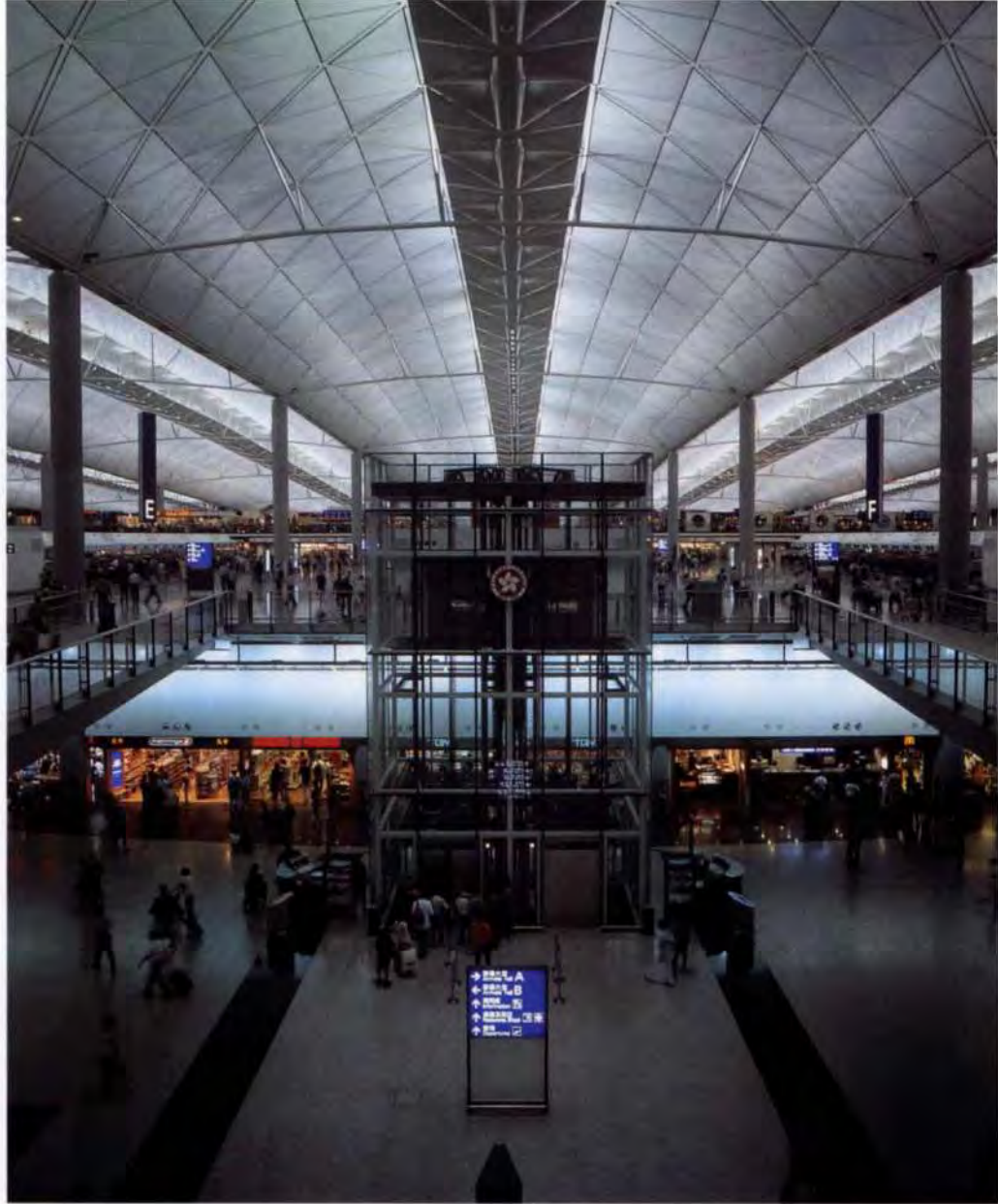
Fire engineering consultant:
Arup Fire

Illustrations:
1, 3: Colin Wade; 2: Sean McDermott
4, 5: Ove Arup & Partners

References

(1) NATIONAL FIRE PROTECTION ASSOCIATION, *NFPA 130. Fixed guideway transit systems*. NFPA, 1990.

(2) BARBER, Chris, *et al. Design for hazard: Fire*. *The Arup Journal*, 26(2), pp22-23, Summer 1991.



3. Part of the retail area at the Terminal Building, showing Cabin Concept smoke canopy.



4 left:
Test fire in mock-up of duty-free area.



5 right:
Fire test on mock-up of HACTL roof structure (see pp14-21)

Platform screen doors

Mike Harley Andrew Harrison Tim Phillips
Armstrong Yakubu, Foster and Partners

Introduction

Platform screen doors (PSDs) were installed on the new railway for environmental reasons - to minimise loss of air-conditioning to tunnels and reduce noise and dirt pollution from the trains. The stations themselves were designed by various architects and although this diversity enhances passenger enjoyment, some elements are common to all to create an integrated and co-ordinated design approach. MTRC appointed Foster and Partners and Arup to design these system-wide elements, thus enabling the PSDs to provide the linking coherence for the stations.

Design concept

Conflicting requirements made the brief for this challenging and exciting project particularly demanding. The PSDs were to be robust enough to withstand crowd, vandal, baggage, train, and typhoon-generated loads. But they also had to be transparent (so as not to compromise revenue from trackside advertising), and light enough to avoid dangerous levels of kinetic energy being generated by their closing.

They also had to be wider than the train doors to accommodate the stopping tolerances of the trains. Finally, they must not compromise the reliability of the whole system or passenger safety (real and perceived).

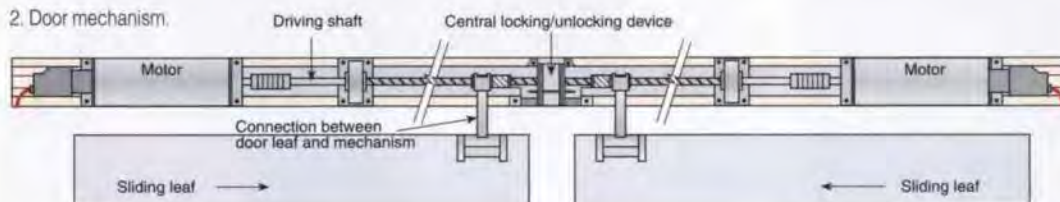
The design team worked closely with MTRC's operations group to produce a design basis document clarifying the system requirements. The doors were to be constructed with stainless steel for maintenance and impact reasons, and with maximum glazing for viewing trackside advertising. The design basis document also clarified all M&E interfaces and requirements.

Installing PSDs along the length of a platform reduces its perceived space, an effect further aggravated by mirroring of the glazing - which also obscures the advertising panels. The solution lay in ensuring that trackside light levels are equal to those on the platform, but this meant that MTRC's plans to leave the trackside wall unfinished had to be reviewed. MTRC eventually agreed to upgrade the advertising panels there, by incorporating new cladding lit by a source underneath the PSDs. Also, an aluminium channel at the head of the doors acts as a service boom, carrying a continuous cylindrical luminaire which lights both platform edge and ceiling, providing indirect and uniform lighting to the platform area. The door indicator lamps act as downlights when the doors open and, together with lights inside the train, additionally illuminate the platform edge to make it brighter than the surrounding areas. These elements create a platform environment that is brighter, safer, and cleaner, and has an enhanced feeling of transparency and lightness.



1. Exploded view of door system.

2. Door mechanism.



3. Screen doors open in front of stationary Airport Express train at Hong Kong Station.

Structural posts were eliminated, which greatly enhances the transparency and lightness of the PSDs and effectively reduces the visible depth of the PSD zone when viewed along the platform length. The door framing itself is curved, reducing visual impact and presenting a 'friendly edge' to passengers moving along the platform. When the doors open, these 'soft' curved edges are presented on both the trackside and platform side.

The doors and screens are supported at their heads by the doorhead mechanism encasement, which acts as a structural bulkhead.

This clear zone between the doors and the platform structure allows maximum flexibility in the positioning and type of door panel, making changes in the door systems easy to suit future alterations in train carriage configurations.

Structural design

The size and framing of the PSDs was kept to an absolute minimum. Toughened glass panels are fixed with structural silicone onto the doorframes so that they are flush with the doors' curved edges. The structural silicone is concealed with fretting. The head mechanism and encasement are also infilled with an openable glass panel with similar flush detailing. Signage is incorporated into the overhead panel, lit by the fitting attached to the door head detail. The whole effect is that of an unobtrusive, minimalist, transparent, and robust system.

Stainless steel was used for the kickboard as well as the framing, whilst the glass is 8mm thick and fully toughened. The initial design had a mid-rail, but later developments removed this to allow almost full-height glass.

The overall configuration of the moving door was defined by both unusual and standard parameters:

- door deflection: limited to 10mm to avoid deflection into the kinematic envelope of a moving train, and to avoid a large setback from the platform edge
- kinetic energy of the closing door: limited to ensure that people trapped in a closing door are not injured, and thus affecting the allowable door weight
- pressure effects from the express trains, and impact loadings from people and luggage
- overall door section sizes: though an aesthetic requirement, the object was to avoid the heavy sections seen in Tokyo and Singapore and offer much more transparency.

As the door closing time of three seconds was set by MTRC and the kinetic energy was limited to 10J, the maximum door leaf weight was 100kg.

The design loadings used were:

- **Train pressures:** 3.26kPa towards the platform and 1.38kPa towards the track, based on a train entering the station at 110kph and leaving at 95kph
- **Crowd loading:** 3kN/m towards the track applied at 1.1m above platform level
- **Impact loading:** 140Nsec applied as a half sine wave of amplitude 2.8kN applied for 0.08sec over a 100mm x 100mm area. This was based on several studies of the force of impacts on safety barriers from vandalism in prisons. This was compared to impact from luggage and the prison riot case was found to be critical.
- **Seismic loading:** 0.07g
- **Wind loading:** for above-ground stations only, 1.2kPa.

The loading combinations for the below-ground case were critical:

- Train pressure towards the track + crowd + seismic
- Train pressure towards platform + seismic
- Train pressure towards track + impact + seismic.



4. PSDs in use on TCL platform at Lai King Station.

For the Airport Express Line, PSDs (designated Platform Edge Doors) are also provided for the baggage-specific train cars catering for the in-town check-in facility.

The hub of the PSD system is the central interface panel (PSC) which links with the signalling system, the supervisory control and data acquisition (SCADA) system, the PSDs, and the other PSD system components. The platform end trackside local control panels indicate PSD status and provide a level of local control to cater for partial system failures.

Operational requirements

The operational parameters - door opening and closing times; average and maximum velocities; closing force; door movement kinetic energy, maximum acceleration; door manual opening force - are interrelated and need to be collectively rationalised to achieve optimum performance. The doors must open and close within a limited period but the forces and kinetic energy that a passenger may be subject to if hit by the doors must be low enough to avoid injury, particularly to the young and the infirm.

The codes and standards in this area were found to be quite limited, with significant variance in what is considered allowable and 'safe'. A maximum kinetic energy of 10J was adopted, but in some existing systems it is near double this (don't get too near train doors in France!). Kinetic energy for the last 100-150mm of door travel (ie 200mm-300mm gap) is particularly critical since this is when someone could be trapped or struck by both leaves. Consequently a reduced kinetic energy of 1J is applied.



5. Detail of doors open.

Because of the nature of the loads and the combination of materials, finite element analysis was used, initially with OASYS-DYNA3D and later by G+D Computing's Strand 6 program. These allowed the team to animate the loading applications to see real time deformations as they spread through the framing.

The design was able to justify using very narrow sections - confirmed by the subcontractor's calculations - though manufacturing difficulties ultimately led to the sections being slightly larger. A full prototype of the doors was subjected to air pressure tests by the subcontractor, and the measured deflections were similar to the original design.

Electrical and mechanical systems

PSD operation is integrated with that of the railway, interfacing with the supervisory circuits controlling the whole system. The key functional requirement was for the PSDs to operate integrally with the train doors in a safe and controlled manner.

Overview

When a train arrives at its correct 'stop' position along the station platform, the door opening cycle is initiated by the train operator pressing a 'doors open' push-button.

This signal is relayed to the PSD system via the signalling system and the PSDs open in parallel with the train doors. After passengers have got on and off, the close cycle is similarly initiated by the train operator. The status of the PSDs is monitored by the signalling system and the train can only depart when all train doors and PSDs are confirmed as closed and locked.

Actuation

To satisfy operational requirements, each doorleaf has its own drive mechanism. The movement of the two doorleaves is synchronised by each PSD's microprocessor-based door control unit (DCU). The actuator is electro-mechanical, with a DC electric drive motor, gearbox, and positively engaged worm drive moving each door. The worm drive is a very tidy solution, and coupled with the common automatic locking / unlocking mechanism at the end of each doorleaf's travel, had much to do with the final selection of the PSD contractor.

Monitoring

The safety-critical 'all PSDs closed and locked' condition is monitored by the signalling system and stops the train leaving if any doors are open or if anything is trapped. Selective data from each PSD's DCU is transmitted to the PSC where it is marshalled for transmission to the SCADA system, together with status monitoring of the motive power equipment and trackside local control panels. This monitored data can greatly assist maintenance, making faults easier to detect and correct, and instigating appropriate preventative maintenance when system performance is seen to tail off.

Electrical

Low voltage DC power for the PSDs comes from local 415V three-phase non-essential supplies, with battery backup allowing limited operation after power failure.

Traction power is supplied via a 1500V DC overhead line with the rails as the return path for the traction current. As a result the potential of the rails (and therefore of any train on them) deviates from earth, resulting in a touch voltage hazard when passengers step off/on the train. To cater for this both the PSD screen system and the platform floor next to it must be electrically isolated from both the train and the station. This was achieved by insulating blocks designed into the PSD fixing points, and a durable insulating membrane installed within a 2m band adjacent to the platform and beneath the platform floor finish. Passengers therefore step/touch a 'neutral' zone as they transit between the earth potential of the station and potential of the train.

Environmental, fire and acoustics

Avoiding condensation on the extensive glass panels was a major challenge; the tunnel air is potentially hot (up to 40°C) and humid while the station condition is controlled to around 24°C/ 60%RH. Various thermal conditions were reviewed against glass thicknesses and types; double glazing was briefly considered, but quickly rejected due to the additional weight. Ultimately a balance was found, with the glass thickness required for adequate structural performance to the PSD panels having sufficient U-value to preclude condensation except under certain extreme conditions.

The PSDs are not designed as a smoke or fire barrier between the tunnel and the station along the platform edge, so both the tunnel and station smoke extract systems assume they will fail. In practice, however, PSDs should provide some benefit for passenger escape under such conditions. While they are also not intended as an acoustic screen, they naturally help to reduce platform noise as trains arrive.

Safety and reliability

These were the key drivers in the PSD design, and hazard and risk assessments highlighted individual hazards and potential mitigating measures. The prime concerns were passengers being trapped by a doorset (which was considered in the design of the 'all doors closed and locked' status signals), being trapped between the PSDs and the train, or dropping between the train body and the platform edge. The latter is a difficult issue especially for curved platforms, since the distance between the platform edge and related PSDs and the train body depends on the train's kinematic envelope and structural gauge which are virtually fixed. In this case, however, large platform curvatures, local relaxations of the train kinematic envelope, and early consideration in the PSD design resulted in a gap which is deemed acceptable, avoiding the need for additional costly and potentially problematic gap sensors.

Credits

Client:
MTRC

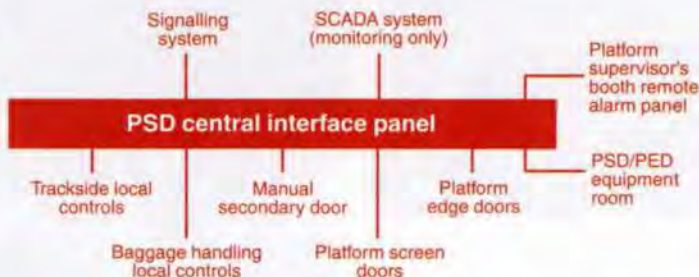
Architect:
Foster and Partners

Project management and engineering design:
Ove Arup & Partners

Quantity surveyors:
WT Partnership

Main contractor:
Faveley Hong Kong Ltd

Illustrations:
1, 2: Jennifer Gunn
3: Colin Wade
4, 5: Damon Yuen
6: Desmond Wyeth



6. System architecture

The acoustic design: Terminal Building and MTRC stations

Sam Tsoi



Introduction

Clear and intelligible speech broadcast by a public address (PA) system is an important safety requirement for transportation buildings, and to achieve this a significant acoustic conditioning of the space is required. Acoustic factors in building design include control of reverberation time (RT), services noise, and external intrusive noise.

The clients' briefs for the Airport Terminal Building and the LAR stations stipulated that the acoustic environment should enable intelligible speech broadcast over the PA system for emergency evacuation - the first time that an objective speech intelligibility criterion for a PA system is known to have been specified for transportation buildings in Hong Kong.

1 left: Curved ceiling panels above the main entrance of Hong Kong Station's in-town check-in Hall.

Arup Acoustics had significant involvement in both the Terminal Building and the LAR stations, including:

- the design and construction phases of the Terminal Building
- system-wide acoustic design of the stations
- detailed architectural acoustic design of Kowloon, Tung Chung, Lai King, and GTC stations
- detailed architectural acoustic and services noise control designs of Hong Kong Station
- detailed services noise control design of Siu Ho Wan Depot
- lead environmental consultant for the Hong Kong and Kowloon Station topside developments.

The dual role of system-wide and detailed design consultant for the LAR projects provided an opportunity to influence the acoustic design at two levels:

- As system-wide design consultant, Arup developed an acoustic design strategy and implemented a noise assurance plan, first preparing recommendations for the system-wide acoustic criteria to the MTRC, and then acting as design checker to verify that the acoustic design objectives had been achieved by the detailed design consultants.
- As detailed design consultant, assistance was given to the individual station design teams on architectural acoustic design, or services noise control design, or both. The architectural acoustic design included RT prediction and sound insulation for plantrooms, whilst the services noise control design embraced the selection of appropriate acoustic treatments for duct-borne noise control of the air distribution system, and noise and vibration control of mechanical and electrical plant.

For the Terminal Building, the main acoustic design aspects were the absorptive and noise-insulated roofing system, the external façades and the services noise control design.

PA system

Speech intelligibility is affected by both background noise level and the acoustics of the space concerned. RT and services noise levels are therefore essential design parameters for speech intelligibility of spaces, and are the relevant criteria for achieving the RASTI (Rapid Speech Transmission Index) requirements - an objective rating of PA intelligibility. The recommended target and acceptance RASTI values for the LAR stations were 0.5 and 0.45 respectively, based on a minimum signal-to-noise ratio of +15dB.

RT prediction

There are no published international standards for RT design prediction, though several academic RT prediction methods exist for theoretical acoustic analysis. Most of these are relatively simple equations, applicable for spaces of a reasonable proportional geometry. Public areas in transportation buildings, however, fall outside this category; the disproportionate spaces of train platforms and concourses will introduce errors in prediction. It is necessary, therefore, to allow for this tolerance in design to ensure that the ultimate targets are achieved in practice.

On these projects the approach to RT design adopted a target-and-acceptance strategy.

The target values formed the basis of the acoustic design by the detailed design consultants, whilst the acceptance values were the maximum allowable limits required for achieving the design intent. These target-and-acceptance criteria must be achieved respectively by design prediction and at commissioning, a strategy which takes account of the uncertainties in the design algorithms and minimises the impacts of any design deviations during construction.



2. Flat panel ceiling over Hong Kong Station's Airport Express Line concourse.



3. Baffle absorptive ceiling above the Tung Chung Line platform in Kowloon Station.



4 right: Half sound-absorptive curved panel and flat panel above the platform at Olympic Station.

A complete set of acoustic design target-and-acceptance criteria was developed and the strategy was implemented.

The target-and-acceptance strategy allows the use of conventional acoustic prediction methods for the complex acoustic geometry of the station space. The 'Sabine' calculation method (named after the 19th century Boston academic who pioneered a scientific approach to acoustic design) was adopted for RT prediction. The volume of space, the surface areas of various surface material finishes, and the absorption coefficients of these materials are the necessary input parameters for analysis.

Services noise control assessment

Services noise criteria apply to all functional spaces of the stations and the external noise-sensitive receiver locations. They should not be exceeded by the simultaneous operation of all mechanical and electrical building services, including regenerated aerodynamic noise, and structure-borne and air-borne noise. Again, the target-and-acceptance strategy was adopted. Noise control design for major plant items like chillers was also developed.

In simple terms, services noise is a source-path-receiver relationship. However, it can be influenced by all components in the system. The most important elements in the acoustic design are to control the source sound power levels and the regenerated noise; this is effected by sound attenuators and by limiting the duct velocities. While this is not generally a problem for a normal building, the sheer scale of the Hong Kong Airport projects meant that over 1000 AHU and fan calculations for each station had to be prepared by Arup (as detailed design consultant) and assessed (as system design consultant). This created a resources problem especially when it was expected that the calculations would need to be revised as the design was being refined.

5 below:
Sound-absorptive fins above the platform screen door glazing in the GTC.



6.
Sound-absorptive curved ceiling panel above the platform area of GTC.



8.
Sound-absorptive roof at Airport Terminal Building.

Arup Acoustics in Hong Kong therefore developed an automated calculation spreadsheet program to enable the significant amount of calculations to be prepared on time. This reduced calculation time by 50%, though of course experienced staff had to check the results.

Implementation

While the implementation of noise control design employed standard, concealed, noise control devices, the physical reverberation control design measures are visible and thus affect the aesthetics of the architectural design. Figs 1 and 2 respectively show the curved profile ceiling in the 10m+ high International Check-in Hall and the flat panel ceiling in the concourse of Hong Kong Station, whilst Figs 3-7 compare the absorptive ceiling designs for the platforms of Kowloon Station, Olympic Station and the GTC Arrivals and Departures platform. The biggest absorptive roof is located at the Terminal Building (Fig 8).



7.
Curved sound-absorptive ceiling above the Kowloon Station Tung Chung Line concourse.

Conclusion

Arup Acoustics in Hong Kong carried out commissioning tests for the RT and services noise levels for the LAR stations, and the same has been commissioned for Hong Kong Station, Kowloon Station, and the GTC. The results showed that almost all the acceptance criteria were achieved, though rectification works will continue.

The results of analysis will serve to refine understanding of complex acoustic space, and the resulting improved techniques will be applied

to the design and strategy for further railway acoustic contracts: the MTRC Tseung Kwan O Extension, the Kowloon Canton Railway Corporation West Rail, and three of the Singapore North East Line stations.

Credits

Clients:
Airport Authority Hong Kong/MTRC
Acoustic consultant:
Arup Acoustics
Illustrations:
1, 3, 6, 7: Mike Chan
2, 4, 5, 8: Colin Wade

Tung Chung Station and tunnels

Colin Wade

Background

Tung Chung is Hong Kong's ninth new town and the first to be built on an outlying island. Situated opposite the new airport on reclaimed land, it is separated by a sea channel some 250m wide across which are three 'Sea Channel Bridges'.

The Government's 1989 Port and Airport Development Strategy study conceived Tung Chung as a housing/industrial support community for the airport, its basic planning and development framework subsequently set by the 1992 North Lantau Development Study. This was developed into a Recommended Outline Development Plan (RODP) envisaging a planned population of 260 000 by 2011; the Government's Territory Development Department (TDD) now expects that to rise to at least 320 000. The town has four basic districts: Tung Chung Central, Tung Chung West, and Tung Chung Valley, and to the east, Tai Ho, on a total of some 760ha of natural and reclaimed land - including the coastal strip for the new highway and railway.

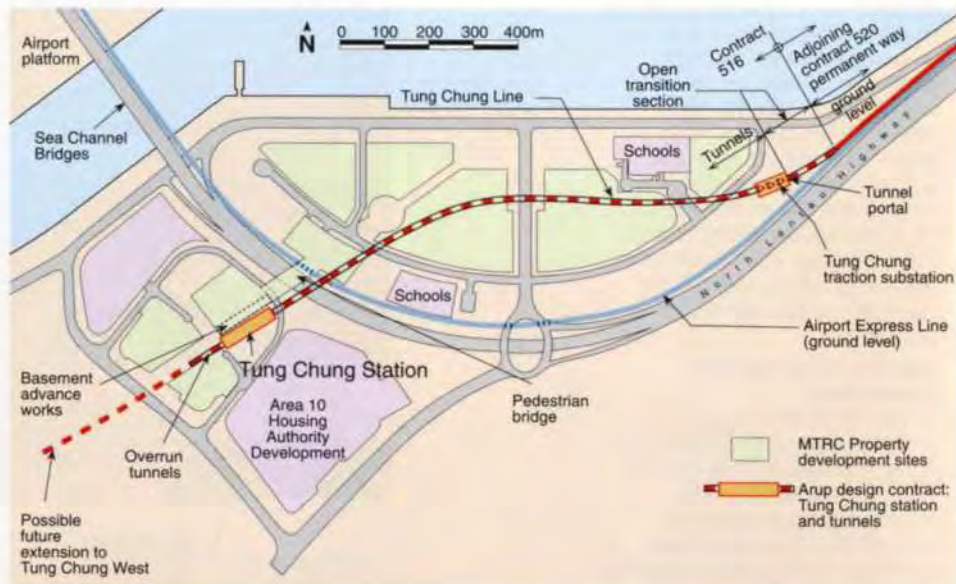
Town centre planning

MTRC's land allocation at Tung Chung is 21.6ha - the largest of its property ventures (c35% of the total portfolio) at the five Lantau and Airport Railway station sites. The allocation at Tung Chung is mainly for housing - some 750 000m² out of a gross 843 000m² total.

The planning study for MTRC was carried out by a team of consultants led by a local practice, Anthony Ng Architects, with Arup providing structural and acoustic input. The final report, issued in June 1992 before Arup's involvement with the LAR began in earnest, established that for practical reasons (including possible future railway extensions), the AEL should cross the new town. Along the north coastline of Lantau the railway parallels the newly constructed North Lantau Highway (NLH) to the airport, with two services sharing common twin track at ground level. East of Tung Chung they separate, the AEL remaining at ground level whilst the Tung Chung Line (TCL) descends into tunnel. A cheaper elevated solution for the TCL was previously studied, but it was decided to go underground for environmental and visual reasons. This also allowed for a long-term plan to extend this line - with a future station at Tung Chung West - looping round onto the airport platform and extending beyond the airport across the sea to the mainland.

The town was seen as a very important visual statement to travellers entering and leaving the airport by road or rail. Flanking the NLH in the town centre will be a hotel and office tower, originally to be linked by a fully air-conditioned bridge across the highway, carrying a level of commercial space with a heavily landscaped accessible roof. The whole would thus form a significant gateway above the AEL and NLH.

Tung Chung's initial public housing estate and support facilities are complete and occupied, with the first phase of MTRC's housing and commercial development at an advanced stage. The station is at its heart - a focal point with adjoining transport interchange facilities, linked directly to the town square and commercial developments.

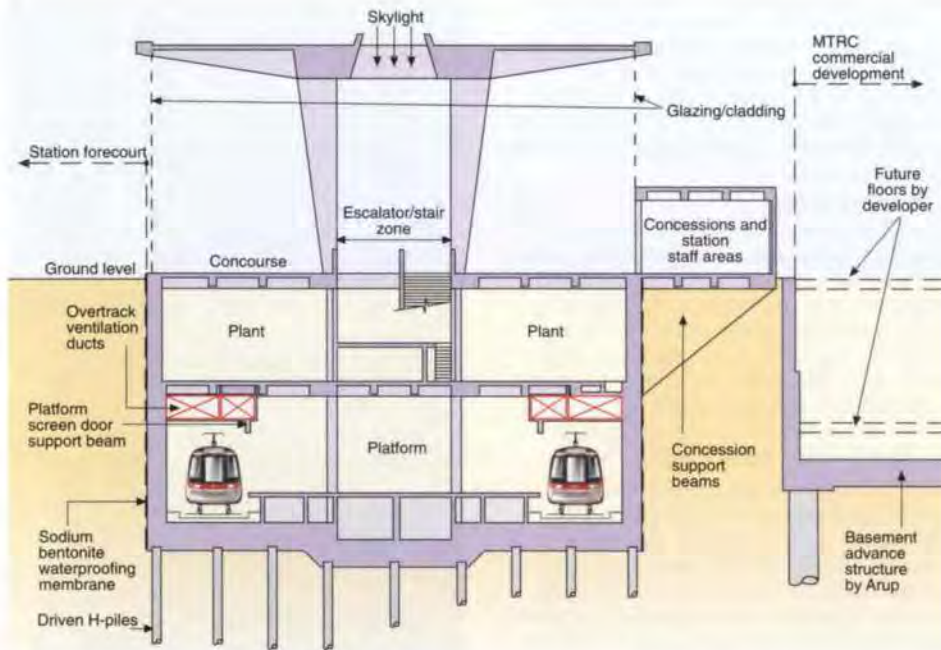


1. Site plan.

2. 1992 concept model of Tung Chung new town showing MTRC development viewed from airport island. The station is left of the half-moon of towers on the right. Construction of much of this is now under way with little change to the concept.



3. Main station entrance area viewed from footbridge; MTRC developments under construction left and behind.



4. Cross-section through station.

Scope of works

Arup's consultancy agreement was signed in December 1992, the original design remit comprising the station; some 1.2km of twin track running tunnels; two overrun tunnels west of the station; an open section as the transition between the tunnel portal and the ground level tracks; and a possible seawater cooling system for the station and the future MTRC commercial developments.

Early client variations deleted the seawater cooling facility, transferred the majority of the traction power facilities in the station zone into a separate traction substation building at the tunnel portal, included related property development enabling works, and introduced into the contract a 36ha reclamation (Tung Chung Phase II) to allow the running tunnels and most of the future property developments to be built. The reclamation was to have been carried out by the TDD but due to timing problems was entrusted to MTRC - and designed by other consultants.

The station has a ground level concourse with two levels beneath, giving direct access to the transport interchange facilities either side of the station. The platform is at the lowest station level, some 11m below ground, and is an 'island' type, with platform and access sandwiched between the twin rail tracks. The intermediate level is non-public, wholly given over to plant, stores, telecommunication rooms, and staff facilities.

Arup role

In contrast to Tsing Yi, Kowloon, and Hong Kong Station, the consultancy agreement for Tung Chung station made Arup, as civil consultant, team leader for the duration of the contract, co-ordinating the architect, building services consultant, and quantity surveyor, and subsequently incorporating the requirements of the Phase II reclamation designer's work.

As with all MTRC's projects, the team leader's role (and other designers') did not include any site supervision or direct dealings with the contractors. However, all except the quantity surveyor were committed to provide a design liaison representative full time on site for a significant part of the works, linking between the site-based MTRC design management staff and the consultants' own design office.

Structures

Station box

Essentially this is a straight rectangular tube containing twin tracks separated by the island platform. The concourse is covered by a large, wing-like roof cantilevering from a double row of tall tapering columns. The concourse level houses station management facilities and staff rooms, as well as some small retail outlets and a mini-bank. Ventilation shafts for both station and tunnel are positioned at either end of the station. A high level walkway across the concourse and station forecourt links to the commercial development and nearby housing.

To match the design work already well under way for Kowloon and Tsing Yi stations, a basic longitudinal structural grid of 12m was adopted, fine-tuned to 11.25m early on by the architect to tie in with the train car and platform screen door module.

Floor structure schemes were investigated and costed, and an in situ two-way primary and secondary beam system supporting a two-way slab proved the cheapest option.

This system was adopted at all levels (with some minor local variations) except for the platform slab, where a one-way solid slab on concrete dwarf walls built off the base slab was used. The two-way system lent itself well to variation, being able to cope with moves or enlargements to slab openings, sleeves, etc, without needing significant trimmer beams. It could also accommodate openings near supports, unlike solutions such as solid flat slabs where restrictions may have been more severe.

The station being the first construction contract on the new reclamation, there were no restrictions from nearby buildings or features, so the station box could be built in an open-cut excavation using battered sides and dewatering wells to keep it dry throughout substructure construction. The station perimeter basement walls could then be built conventionally, with full access to both faces allowing a sodium bentonite membrane (an MTRC requirement) to be easily applied to the external wall faces.

Although the station could have lent itself to some prefabrication, like much of HK's construction industry, the structure was designed as wholly in situ concrete and no serious alternatives were put forward by tenderers.

Station roof

Tung Chung relates closely, both visually and functionally, to the new airport, so it was felt that the station should reflect the feeling of flight and have as much natural light as possible. Initially, various lightweight steel roof schemes - tubular trusses, castellated and solid web girders - were examined, with support options ranging from simple tubular columns to tree clusters, V-shaped columns, forked columns and combinations of concrete and steel tubes. Whilst the steel options had individual pros and cons, there were two common disadvantages for MTRC - cost, and long-term maintenance. In consequence, several concrete schemes were investigated, based on the 'wing' concept, and the final built shape cantilevers some 8m from the columns. A further advantage of concrete is that it assists in counteracting flotation of the station.



5. Island platform with columns clad in vitreous enamel steel panels. The glass-enclosed lift is customised for each station but developed from system-wide generic principles developed for MTRC by Arup Associates.

After careful study of all the options, MTRC opted for a concrete scheme in which the roof is a slab and ribbed beam structure; the beams taper outwards in plan and elevation to enhance the wing effect. A central, continuous clerestory rooflight and glazed walls at both ends of the station allows natural light to penetrate. From a structural engineering viewpoint the roof soffit shape and concrete finish would have been visually very attractive but, as completed, much of the wing areas are hidden by an acoustic ceiling, in line with the architect's early concept sketches.

Running tunnels

The tunnels were conceived as a simple twin box - each tunnel accommodating a fireman's walkway as well the usual array of cabling for power, signalling, and communications. Each tunnel is approximately 5.4 x 5.4m internally, except for the U-shaped open transition section.

Like the station, there were no restrictions on land take when construction started, and the running tunnels and open transition section were constructed in open cut excavation for their entire length. This again allowed full access for the waterproofing membrane to be easily applied. The tunnels are curved in plan to follow the requirements of the new town layout, and early discussions were held with an experienced international formwork manufacturer to confirm that they could be built rapidly using travelling formwork if required. However, during bidding, the tenderers did not suggest any variations to the design or arrangement and the contractor adopted a relatively simple system using sets of straight shutters on a travelling bogie.

The majority of tunnel length is identical except at the scissors track crossover box near the station, where the central dividing wall disappears, giving an 11m clear span roof. Elsewhere, the boxes widen out to accommodate impulse fan chambers by the track for tunnel ventilation; here the tunnel roof is supported by columns close to the tracks. These had to be designed for train impact, and for complete removal of any one column in the extreme collision condition.

Traction substation

Some 26 ancillary buildings and structures of varying size and shape are sited along the whole LAR: most are traction substations or ventilation buildings or both, and mostly were designed by MTRC's Architect's Department. MTRC's policy was, as far as possible, to give them all a similar identity, particularly in terms of exterior colour (dominated by a dark green tiled finish), although the Kowloon Ventilation Building (see pp44-51) was allowed its own special identity.

The Tung Chung traction substation (or TUT in MTRC parlance), was in the corporate style and, being on fresh reclamation, had several schemes considered for the most cost-effective foundation solution. It is a single-storey building 66m long x 18m wide above ground with additional basement areas for water tanks, pumps, impulse fans, and other equipment.

Arup proposed that it be placed directly above the running tunnel boxes, thus obviating the need for foundations and using the tunnel as a raft. Whilst some special treatments were needed to avoid the penetrations through the tunnel roof for services - in particular drainage for floor trenches - the concept was simple and effective.

6. The concourse from the east: central clerestory rooflight is accessed for cleaning and maintenance by a mesh catwalk, which also contains some services.



Geotechnics and foundations

Station zone

The station, and crossover tunnel immediately to the east, are within Tung Chung's Phase 1 reclamation, carried out during the initial station design period in 1992. MTRC's intention was to found the station in the deep compacted reclamation sand fill, which was specified to provide a consistent bearing capacity of 15MPa from 2m depth downwards; the sand fill in the station site varied from 7m to 23m, following the original seabed contour.

The station was conceived as a simple 'floating' box with a 1.7m thick raft incorporating heels to help resist flotation by mobilising soil wedges above them.

When reclamation was complete, however, MTRC's precontract boreholes revealed a different picture. Instead of a clean sand fill giving 15MPa bearing capacity, it proved to be heavily contaminated by silt, with bearing values significantly lower than could sustain the station design. As design for tender documentation was under way, a rapid reassessment of the station foundation was carried out. There were five possible alternatives: complete removal and replacement of the contaminated material; ground improvement by a close grid of stone columns; or founding the station on mini-piles, large diameter bored piles, or a close grid of driven steel H-piles. Cost and programme comparisons showed the latter to be the most attractive option as H-piles would also allow the base slab thickness to be reduced to 1.4m and less heavily reinforced. In addition, as the H-piles work in friction in the subsoil beneath the sand fill, they can also resist uplift - so the heels extending beyond the station box could be largely eliminated. The H-pile option was adopted, incorporated into the tender documentation, and the contaminated soil left in place.



7 left:
The concourse from the west:
roof soffit and side cladding to central rooflight
are perforated metal acoustic panels.



8 above
Completed in situ concourse roof structure
with acoustic ceiling framing under way.

9.
Twin box cut-and-cover running tunnels under construction in the new
reclamation with the hinterland of Lantau Island behind.



Running tunnel zone

As this portion falls in the Phase II reclamation, the specification and supervision came directly under MTRC's remit within Contract 516.

The deep compacted sand fill for this zone met all specification requirements and the tunnels have remained as 'floating' boxes within the 15Mpa bearing capacity criterion. Due to a large dip in rockhead along the alignment up to 90m below ground, there is a significant difference in the superficial soil deposits in which the tunnels lie. Interactive soil-structure longitudinal analyses were carried out to ensure long-term settlements could be coped with. These were revisited and refined as MTRC's settlement data became available between reclamation completion and commencement of tunnel construction. Longitudinal tunnel box reinforcement has been detailed to reflect the predicted long-term settlement. Also, the base slab was cast at an initial level higher than the design level to allow for settlement effects.

Early investigations were also undertaken with MTRC to ensure an economic sequence of the open cut excavation to balance cut-and-fill, and requirements for excavation, base slab, walls, and roof sequencing were added to the contract document to avoid settlement problems during construction.

Close monitoring of tunnel settlement was carried out and post-completion monitoring indicates that all is within the prediction.

Station and tunnel construction

As the east end of the station and crossover tunnel box are under the NLH, MTRC was obliged early on in Arup's commission to incorporate a portion of the station and crossover box into the government's NLH Highway Contract HY/92/05 as entrusted work, to ensure no delays would occur to the completion of the airport road and rail links. This involved rapidly designing a portion of the station as a minimal shell to provide the basic box of the station and tunnels and avoid building too many elements at a stage when architectural and services concepts were not finalised. Sufficient drawings were incorporated into Contract HY/92/05 and supplemented later by the modifications caused by introducing H-piles in the Contract 516 portion of the station. Contract HY/92/05 began first, and this portion of the station box and crossover tunnel was rapidly built in open cut. The remaining station structure and tunnels and all supplementary structural work inside the initial box were built directly for MTRC under Contract 516.

The transition between the crossover tunnel - founded on H-piles - and the 'floating' main running tunnels was achieved by a stitch joint. The team working here on the Tung Chung project were fortunate in being able to develop these types of joints in collaboration with colleagues working on Kowloon and Hong Kong stations, where similar problems were being encountered. The stitch allowed most settlement in the adjoining tunnel sections to be taken up before rail track laying began. The joint incorporates a 'special' gasket around the tunnel box, thus allowing differential vertical movement whilst resisting groundwater penetration after tunnel backfilling was complete and dewatering switched off. As late as possible the tunnel roof, floor, and walls were concreted up with additional reinforcement spliced onto projecting bars to cater for long-term longitudinal bending across the joint.

From a delayed signing in late November 1994 site work started with dewatering and bulk excavation in early 1995. Station topping-out was celebrated on 18 December 1996 and the station was completed in full working order for a public open day on 12 June 1998 prior to the railway opening ceremony on 21 June.

Conclusion

Domestic underground mass transit stations may look deceptively simple to the general public passing from concourse to trains. However, these station boxes house much ventilation, electrical, mechanical, communications, and signalling equipment both above and below ground to maintain system safety and security whilst providing a fast, clean and efficient service.

Tung Chung is no exception and it is to the credit of all the consultants' design teams, the client's design management and construction supervision team, and the contractors that this complex civil engineering structure with its tunnels, ancillary structures, and associated property enabling works, plus a significant piece of reclamation, was constructed in just over three years from contract signing to public open day.

Credits

Client:
MTRC

Team leader; civil and structural engineer:
Ove Arup & Partners

Architects:
MTRC Architects Department in association with
Rocco Design Partners (Contract 516)
Anthony Ng Architects Ltd (Tung Chung Masterplan)

Mechanical & electrical consultants:
J Roger Preston & Partners (Contract 516)

Quantity Surveyors:
Widnell (Contract 516
and Contract HY/92/05 Entrusted Works)

Main contractors:
AOKI Corporation (Contract 516)
China State - Leighton - Hochtief Joint Venture
(Contract HY/92/05 Entrusted Works)

Illustrations:
1, 4: Bird Wong / Jennifer Gunn
2: Anthony Ng Architects
3, 5-9: Colin Wade

Tsing Yi Station, viaducts, and development

Andrew Davidson
Sai Lung Ho Naeem Hussain
Charles Law Leslie Toong

Introduction

The setting for Tsing Yi Station and its associated railway viaducts is a hilly island of some 960ha, separated from the mainland of north-west Kowloon by an 300m-wide strip of water known as the Rambler Channel.

The island was largely uninhabited until the early 1960s, when government leases allowed small industrial units, oil tank farms, and a large power station to be developed. Access was only by marine craft until completion of the first high-level road bridge in 1974, which paved the way for rapid development and reclamation, much of it on the east shoreline. This side of the island is now partly occupied by large public and private housing estates and a growing town centre.

Three road bridges are now in place as well as the Rambler Channel Bridge - MTRC's new 1.1km, two-level four-track railway bridge carrying the LAR between Tsing Yi and the Kwai Chung district of north Kowloon.

Tsing Yi Station is on the north-east tip of the island on the shoreline of the Rambler Channel. Lying approximately midway between Chek Lap Kok and central Hong Kong and on the southern boundary of the New Territories, this is an important strategic location on the new railway. Serving both the Tung Chung and Airport Express Lines, the Station is one of the 'big three' on the LAR, designed to handle an initial estimated passenger flow of 17 000 people per hour, rising to 24 000 in 2021.

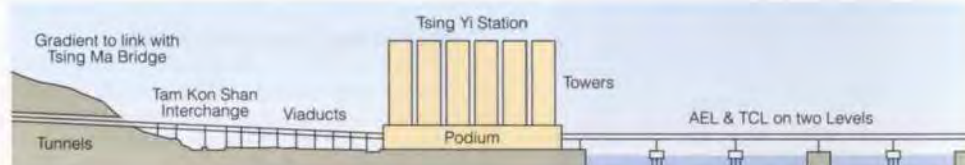
To the east, the Station connects directly with the Rambler Channel Bridge. To the west, the viaducts link the Station to the tunnels which pass through the island and connect directly with the Tsing Ma suspension bridge. Due to the rail alignment on the Tsing Ma and Rambler Channel Bridges, Tsing Yi is an elevated station, with four tracks running through the podium at high level.

Whilst some of MTRC's revenue is generated by fares, retail concessions, advertising spaces, etc, a significant source of funds for capital investment is from joint venture property development - a method used successfully by the Corporation since the inception of the MTR system in the late 1970s. Of the 38 stations on the system prior to completion of the LAR, 19 have associated property development with a total of 31 366 residential flats; 194 300m² of offices; 245 700m² of commercial space; and 139 400m² of government institutional and community area.

The development at Tsing Yi comprises residential and commercial / office space, and yields some 291 000m² of gross floor area - 10% of the total LAR property packages. The six-storey Station podium is the platform for 12 high-rise residential towers, accommodating some 10 000 people in 3500 units.

Arup's involvement at Tsing Yi can be split into three distinct elements:

- **Station podium:** structural engineers for the Station podium structure, up to and including its deck, from preliminary through to detailed design and construction
- **Development:** structural engineers for the commercial development, the public transport interchange, and the preliminary scheming of the residential towers.
- **Viaducts:** lead engineering consultant for the 420m long multi-level and multi-track viaducts between Tsing Yi Station and the Tam Kon Shan tunnels to the west.



1 & 2:
Site plan (top)
and Section.

3 right:
The site viewed
from Tsing Tsuen
Bridge in 1992,
before construction.



4 left:
Model of Tsing Yi Station
showing the 12 residential towers
on top of the Station podium
viewed from the east.

Station podium

Unlike the other LAR stations to which Arup contributed, at Tsing Yi the podium is constructed almost entirely above ground on reclamation laid in the mid-1980s. (The exception is the sea-water pumphouse, which required a 20m deep excavation.) This generated a very different set of design criteria from those for the other station projects, which are predominantly underground.

The site covers approximately 5.4ha, with a building footprint of around 50 000m². There are seven floors including ground, with an average floor-to-floor height of 5.5m. The height of the development podium above external ground level is 34m, making it one of the tallest in Hong Kong.

The AEL and TCL concourse, platforms, and tracks are located respectively on the second and third levels. Commercial and retail areas totalling some 60 000m² are also on these floors but separated from the Station by four-hour fire-rated partitions. Car parking for 1350 vehicles is provided on the fourth and fifth floors.

The podium also accommodates the MTRC's Operations Control Centre: a triple-height 6000m² nerve centre for the entire LAR.

Tsing Yi's design needed to emphasise its significance as one of the major stations on the LAR, together with Hong Kong and Kowloon. Features include the extensive glazed walls around the five-storey atria on the north and north eastern elevations. The main Station lobby called for a large atrium in keeping with the tone and design criteria throughout the AEL, and this imposed a number of planning, architectural, and fire engineering challenges.

The adjacent Rambler Channel was exploited in the early planning stages: the seawater cooling system for the Station and development was agreed upon, and the only major underground structure, the pump house, was integrated into the structure.

To reduce initial costs, MTRC's original design consultancy agreement required only part of the Station to be built in the first stage, leaving the entire northern portion of the podium to be built by a future developer. However, due to the transport interchanges in and around the Station, discrete demarcation between it and the development portion could not be made without major planning constraints. After appointment, the consultants jointly recommended the MTRC to plan and build the entire Station in one stage, leaving enough flexibility for future developments.

Residential development

12 residential towers from 33 to 37 storeys rise above the Station podium, each supported on 12 circular columns 2.4m in diameter. Arup's brief was to design the podium structure to support the towers, at a stage when the development control documents were still being prepared for tender by MTRC's Property Department. The design had to allow for the future developer possibly changing the tower shape and even the orientation of the towers.

However, the tower footprint area and locations were essentially fixed by MTRC's development control brief and master layout plan. The detailed structural design for the towers was eventually carried out by the developer's consultant team. The podium also supports residential development facilities including two swimming pools, an artificial beach, tennis and squash courts, emergency vehicular access roads, landscaping, and a copper-clad curved concrete roof covering the atrium above the AEL departure concourse.

5. The Station podium and viaducts during construction.



6 below:
Station under construction between tower block areas - on the right the 2.4m diameter columns await tower construction. Centre rear is the copper-clad curved concrete roof covering the atrium above the AEL departure concourse.



7 right:
Residential tower development under construction. Along the northern elevation, adjacent to Tsing Tsuen road, a 300m long, 12m wide cantilever noise canopy framed in structural steelwork is provided to lessen the effect of traffic noise on the residential towers above.





8 above:
A 35m long, 5m wide feather, the work of artist Neil Dawson, is suspended over the third floor AEL departure concourse.



9 & 10.
The MTRC entrance atrium.

Circulation

Included in the government's planning brief was the requirement for adequate public access into the Station. Pedestrians use three footbridges, two of them connecting the Station with the transport interchange, which were designed and constructed under the development contract.

There are also several vehicular access points. The north side of the Station is bounded by the existing Tsing Tsuen Road Bridge, from which a new slip road enters the building at fourth floor level allowing access to the AEL departure concourse drop-off at third floor, and car parking on the fifth floor for residents. Access for delivery trucks and emergency vehicles to the podium roof itself is also provided.

The combined result of these requirements is 11 separate ramp structures in the building, with a total length of some 2km. Some provide access between only two floors, whilst others work their way through the building linking several floors.

Two spiral ramps approximately 40m high provide uninterrupted access and egress to the podium deck for both private and emergency vehicle access.

Structure

The Station's structural complexity was increased by atria being incorporated throughout the building, and by the large glazed walls and the curved roof above the AEL arrival concourse area. This, combined with the inter-level access required for people and vehicles, turned an initially relatively simple building into a structural concrete framework with many complexities to be solved.

Framing

The podium structure is a series of reinforced concrete sway frames designed to support dead and live gravity loading as well as bending moments and shear forces arising from wind or seismic action.

Although Hong Kong is in an area of low to moderate seismicity, there are no seismic building regulations. Arup was commissioned by MTRC at an early stage to carry out a seismic assessment as it was felt that the LAR projects should be subject to a seismic design procedure, considering the relatively long specified design life of 120 years. This commission studied above-ground and buried structures on the four Arup LAR stations, as well as a liquefaction potential for the sites themselves. Except for the railway zone within the podium (which has no towers above), wind load is the controlling case. However, as at Kowloon Station, the concrete frame was detailed to provide additional ductility in a seismic event.

The reinforced concrete moment frames are separated by movement joints throughout the height and width of the structure above ground, and at foundation level are connected by a series of tie beams between the pile caps. The main beams and columns are set out on a 12m x 12m grid, with secondary beams at third points in both directions. Two-way spanning slabs, varying in depth from 125mm to 200mm depending on loading and fire resistance periods, provide the infill between the beams.

One of the main requirements governing the slab design was the need to provide a four-hour fire separation between the Station and the commercial areas, both horizontally and vertically. The main beam sizes are based on a standard 1.5m wide unit with depths varying from 700mm in general areas to 1.6m for those areas supporting the tower blocks. Column diameters vary from the standard 'small' 1.2m to 2.4m under the tower blocks. As the vertical structure of the towers is totally different from the grid and framing of the podium, they are carried on transfer plates supported by the podium columns on the 12m grid.

The structure is split into 11 areas by movement joints, so positioned as to isolate areas supporting tower blocks from those without towers, to account for different magnitudes of predicted movements. The railway alignment effectively splits the Station podium in two, north to south. The operating railway zone - the tracks, platform, associated areas, and their support structure - is also isolated from the rest of the structure by movement joints.

Arup did some preliminary design on a tower block scheme in order to design the podium itself and ensure a robust but economic structure that could accommodate some small variations in the future (in the later stages of the project some variations did occur - described below).

The podium structure is designed to resist both the horizontal and vertical reactions from these towers. The movement joints are designed to accommodate predicted movements due to shrinkage, creep, thermal and wind effects of up to 70mm opening and 30mm closing.

Foundations

Unlike Hong Kong, Kowloon and Tung Chung Stations, this site is on older reclamation, placed in the mid-to-late 1980s and used for some years as a lorry park. Boreholes revealed rockhead from 4m to 18m below ground. Intermediate soils comprise the reclamation fill, marine and alluvial deposits, and completely decomposed granite.

Column loads are high due to the towers and podium. Bored piles were chosen except in areas of high rockhead where a small number of reinforced concrete pad footings could be used. Pile diameters range from 1.2 to 2.5m and are either placed singly under columns or grouped below large pile caps.

The article on Kowloon (pp44-51) describes the pile capacity enhancement obtained by on-site full-scale pile testing. Tsing Yi followed an identical sequence with a similar test regime, which led to the acceptance of an increased pile capacity by the use of end-bearing and rock socket friction for compression loads. As the Station has no basements, tension loads are not present. With a total of 637 piles for the Station podium, large savings were achieved for MTRC. Bored pile construction methods were similar to Kowloon Station with 15 reverse circulation drilling rigs on site at the peak production stage.

Tsing Yi development

The podium accommodates a commercial centre outside the railway operating zones and a separate public transport interchange building. Arup's involvement included structural engineering for the alterations and amendments (A&A work) to the podium structure for the revised architectural development layout required by the consortium who had won the rights to develop both the residential and commercial parts of the Station. MTRC's lease conditions required the developer to build the public transport interchange and, as this was deemed part of the Station, Arup was commissioned to carry out the geotechnics and structural engineering.

Commercial centre

This comprises four levels (ground to third floor) in the north-east area of the podium. It has a separate identity, while sharing convenient access and integrated facilities with the Station complex. The centre's main floor is at first floor level for easy access via footbridges and walkways from the surrounding areas. The ground floor is also connected to a landscaped promenade along the Rambler Channel.



Other areas of the commercial centre are placed over three to five levels distributed around the atria, particular the north-east atrium which has a five-storey high glass curtain wall allowing views over the Rambler Channel. The atrium concept provides an environment where natural lighting can filter into the entire commercial centre.

The development also includes 46 170m² of retail area providing a strategic mix of shops, food outlets, and entertainment facilities, destined to become a major attraction in Tsing Yi town centre. A two-level car park for the exclusive use of the commercial centre has 200 spaces and direct access to the centre via lifts. Other facilities include 47 commercial loading and unloading spaces, a kindergarten and a nursery.

Podium A&A

Following the appointment of the development consortium, MTRC's original concept for the commercial and retail areas was taken over by the development architect, who had to take into account the developer's preferences and many commercial requirements to make the area attractive to tenants. The outcome of this was substantial alteration works to the built structure, including breaking out of areas and partial infilling of atria to create more space.

The developer also required additional floors be added to the residential towers requiring the podium structure to be re-analysed to ensure it could accommodate the increased loading.

Public transport interchange

The interchange is a single-storey reinforced concrete building of some 9500m² on a separate site north of the Station. It includes an open bus terminus on the roof, a lorry park below at ground level, and an adjoining open-air minibus and taxi facility. It is linked to the commercial centre and the Station concourse at the north entrance by covered footbridges.

Two ramps provide vehicular access to and from ground level. The bus terminus has 14 drop-off / pick-up points and 28 stacking bays for double-decker buses, passengers being protected at each pick-up point by a continuous canopy connected to the footbridges. The minibus bay, west of the interchange at ground level, comprises three minibus lanes, each with three parking spaces and a taxi drop-off/pick-up lane. The lorry park provides some 100 parking spaces, with other spaces for recovery vehicles.

Structure

The bus terminus is a 250mm thick reinforced concrete one-way spanning slab supported by a series of secondary reinforced concrete beams, 750mm wide by 1.75m deep, and primary reinforced concrete beams, 1.5m wide by 2m deep, spanning up to 20m to accommodate the lorry park requirements below. Due to the high superimposed live loads, long spans, seismic requirements, and the need for a structure without cores and shear walls to accommodate lorry circulation, the structure is a moment-resisting beam-and-column framework supported mainly on bored piles and - where rockhead is high - on pad footings.



12.
Public transport interchange under construction. Beyond is the district of Tsuen Wan across the Rambler Channel.

13. Prestressed concrete box viaduct superstructure under construction.



15 above:
Viaducts at
Tam Kon Shan
Interchange.

Tsing Yi viaducts

These are 420m long multi-level and multi-track structures, up to 25m above ground level, linking the west end of the Station and the Tam Kon Shan tunnels. The two tracks of the AEL and the TCL and tracks for sidings exit at two levels from the Station. These six individual tracks then merge to become three tracks into three separate tunnels in the hillside. Two carry the AEL and TCL, whilst the third is for sidings, also in tunnel. The viaduct configuration leads to 13 and 14 spans on the individual tracks.

Arup's design submission bid was a mixture of open decks and enclosed boxes similar in concept to that later adopted for the BERTS project in Bangkok¹. However, due to the complex railway alignment requirements, size, and irregular spans, the closed box solutions were not taken forward after Arup's appointment. The high level of the viaducts, combined with a multi-level and multi-track configuration, led to an open deck solution with noise-absorbing concrete parapets. Supports are portal type piers with varying numbers of vertical and horizontal members. The piers are the most dominant visual element of the viaducts and these were studied in detail and sculpted to add visual interest and lessen their impact on the surroundings. A steel portal frame clad with transparent panels was provided west of the Station to give acoustic screening to the residential towers immediately above.

The viaducts traverse a varied topography. Immediately west of the Station the decks span a dual carriageway and cross a flat grassy area adjoining a heavily wooded slope. Before connecting with the hillside tunnels, they again span a very busy dual carriageway exactly at its junction with a large roundabout - the Tam Kon Shan Interchange. Due to these features it was not possible to adopt a single foundation system. A mixture of traditional Hong Kong hand-dug caissons and large diameter bored piles, both founded in rock, was used, with the piers springing from pile caps.

The superstructure is an in situ prestressed concrete box continuous over five or more spans with movement joints at two pier positions, tunnel abutments, and at the junction with the Station. It was built by the 'span-by-span' method and, to avoid any obstructions at ground level which would have seriously disrupted traffic, the decks were cast mainly on formwork supported by steel trusses spanning between completed piers and clamped to portions of completed deck.

14.
Pier details of viaduct
near tunnel portals.



Generally the spans are 29m, increasing up to 44m, the total length of the prestressed concrete box superstructure being 1355m. The deck widths vary - the single track sections are some 5.5m wide over parapets, while the merged sections increase to 15.5m. Deck depths were standardised for visual reasons and economy of formwork: up to 30m spans the overall structural deck is 1.6m deep with 400mm thick webs, whilst for spans above 40m it increases to 2.2m with 450mm thick webs.

Conclusion

The final outward appearance of the podium at Tsing Yi Station belies an extremely complex interior. Few buildings (if any) of this magnitude house two levels of an urban railway passing through the middle, and provide such a range of other functions as commercial, retail, parking, loading, and roadways. Arup's design and drafting teams in Scotland, London, and Hong Kong faced a difficult task throughout the project, producing and co-ordinating a vast amount of information and coping with the inevitable changes and problems such a complex structure brought about.

That task is now over and the building, with its commercial centre and transport facilities, will become a focus for Tsing Yi island's further rapid development in the years to come.

Design management

The detailed design was split into packages with the substructure, superstructure, and viaducts designed in different offices.

The substructure package was designed and detailed in the Hong Kong office, and the superstructure - the bulk of the work - in the Glasgow office. Detailed design of the viaducts was carried out in Hong Kong and London by the firm's bridges groups, with detailed co-ordination in Hong Kong.

With MTRC, the architect and the M&E consultants all based in Hong Kong, control of the general arrangement drawings remained in the Hong Kong office, putting a strong emphasis on co-ordination and liaison with the remote design offices.

The detailed design of the podium structure required over 1100 reinforcement drawings including bending schedules.

These were downloaded electronically to Hong Kong and plotted for issue. The time difference between Hong Kong and Glasgow of seven or eight hours (depending on the time of year), meant that there was a 'window of opportunity' for telephone conversations, needed particularly at times when a number of complex changes were occurring.

MTRC's design management team was well-established and organised, with the property and railway departments working closely together to develop the planning of the Station. The weekly design team meetings with the client and other consultants meant that any problems were resolved quickly and cost-effectively, with MTRC taking a pro-active role in the decision-making process at the meetings

16. Viaducts crossing Tam Kon Shan Interchange with Airport Express train.



Reference

(1) FORSTER, Robin, and LOADER, John. International working: BERTS. *The Arup Journal*, 30(1), pp4-7, 1/1995.

Credits

Station

Client:
MTRC

Architect & lead consultant:
Wong Tung & Partners

Civil and structural engineer:
Ove Arup & Partners

M&E consultant:
J Roger Preston & Partners

Quantity surveyor:
Davis Langdon & Seah Hong Kong Ltd

Main contractor:
Maeda-Kumagai Joint Venture

Podium commercial development, A & A works and public transport interchange

Client:
Shinta Ltd

Architect:
Wong Tung & Partners

Civil and structural engineer:
Ove Arup & Partners

M&E consultant:
Meinhardt Consulting Engineers

Quantity surveyor:
Levett & Bailey

Main contractors:
Chun Wo Building Construction Ltd (A & A Works)
B + B Construction Co Ltd (Public transport interchange and walkways)

Viaducts

Client:
MTRC

Lead consultant and civil and structural engineers:
Ove Arup & Partners

Quantity surveyor:
Davis Langdon & Seah Ltd

Contract:
Downer-Zublin Joint Venture

Illustrations:

1, 2: Nigel Whale
3, 5-7, 9-16: Colin Wade
4: Wong Tung & Partners
8: Gareth Jones

Kowloon Station, tunnels, and developments

Eric Chan Belzazar Fajutagana Robert Hale Clive Holman Ian Hooper Steve Hope John Lucas
Martin Mok James Musgrave Derek Smyth

Introduction

Kowloon is the largest of all the stations on the LAR, serving both the AEL and TCL, and as the main terminus from the Kowloon urban area to the airport it also has check-in and arrival facilities for air travellers. It is thus seen not just as a station but as an extension of the airport itself, forming part of a major integrated interchange between the railway and other transport modes including taxis, buses, and cars.

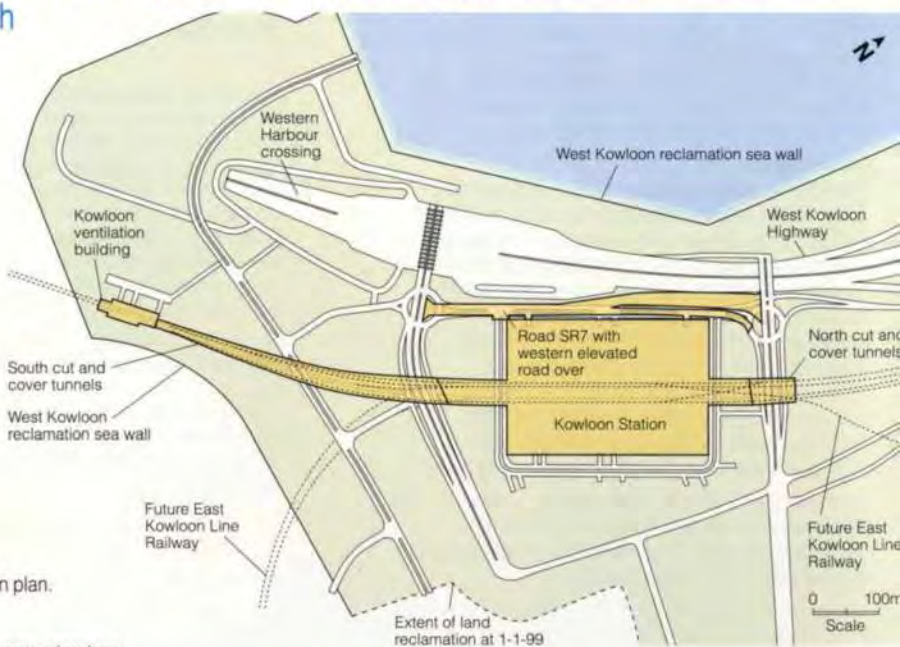
As the Station and tunnels are built on a vast area of freshly-reclaimed land, the project is unique among Hong Kong's underground stations. With a site in some 30m of sand fill very close to the harbour, and a water table only 2.5m below ground, MTRC's concept study consultant team envisaged the Station and tunnels enclosed by a diaphragm wall. Given the size and plan shape of their proposed station layout, a considerable length and depth of costly wall formed the basis of the concept study Station box and tunnels.

Arup's involvement with Kowloon began in early 1992, when several staff were seconded to MTRC for short terms while the concept design was being finalised and MTRC was building up a full design management team. During this secondment stage, Arup prepared an alternative proposal to construct the Station and tunnels using open-cut excavation. MTRC received this with great interest, and adopted it as their preferred method for in-house project planning and costing. However, when detailed design consultancy bid documents were issued by MTRC in mid-1992, the concept study proposals, including the diaphragm wall assumption, formed the briefing and scope documents.

In response, Arup's submission for the civil and structural engineering consultancy in August 1992 again proposed an open-cut method as a far simpler and more cost-effective alternative to the concept design.

The whole site extends over 13.6ha, accommodating the Station, the residential, commercial, retail, and hotel functions, and the transport interchange. These requirements were set out in the briefing documents and on the drawings produced as part of MTRC's concept design study. These drawings included the scale and facilities the Station was to offer, defining all the required elements and placing them in a functional geometric arrangement.

They also included the 'developments' (non-core railway projects) which were part of the Station masterplan. These documents were the basis of the detailed design consultancy bids issued by MTRC for architectural, M&E, quantity surveying, and civil and structural engineering services, and subsequently formed part of the contractual agreement documents between each successful consultant and MTRC.



1. Location plan.

2. Station superstructure



Arup's involvement at Kowloon included:

- the Station
- the Kowloon Ventilation Building (KVB)
- north and south cut-and-cover tunnels
- the Western Elevated Road (WER) and road SR7
- the Station development studies.

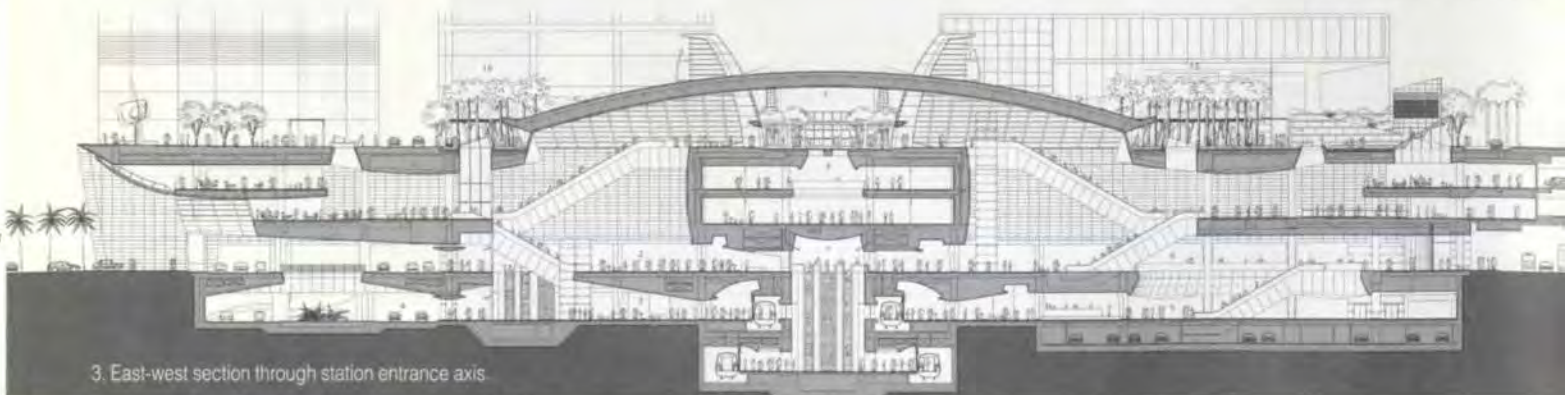
Except for the Station development studies, all these were included under a single detailed design consultancy agreement signed with MTRC in October 1992.

Kowloon Station planning

The Station and its future development area form a major piece of urban architecture, and MTRC were fully aware of its high profile. The design was won by Terry Farrell & Partners, who were already carrying out other work in Hong Kong; their architectural design bid proposal differed significantly from other competitors and was a deserved winner. The form and geometry from the concept study were completely re-organised, simplified, and all Station functions rearranged to fit into a 300m long and 180m wide structure known as 'the box'.

Main text continues on page 46 ►

3. East-west section through station entrance axis





4. Station structure under construction, December 1996: south cut-and-cover tunnels on the left; north cut-and cover tunnels just beyond end of Station.



5. Station excavation complete, with TCL base slab and perimeter retaining walls under construction. Bored piles exposed by the open cut excavation can be seen either side of the box.



6. Current Masterplan at podium deck level. The First development Package (Towers 9-14) and Kowloon Station Square (between Towers 20-23) are under construction.

Pedestrian, traffic, and transport planning

Arup's involvement with this part of the project also started in 1992, as traffic sub-consultants to Terry Farrell & Partners for the masterplan design. Initially this mainly involved assessing traffic impact from the Station and its associated property development on the surrounding road network, and scheme design study for the Station. A transport master plan was recommended, to accommodate transport facilities relating to the Station and to the development. As the Station project progressed to detailed design, Arup continued as detailed design sub-consultants to the architects for Station planning works, and as traffic engineering specialists for the civil design works.

Station planning

A large number of users from the two railway lines was predicted, and initial tasks included reviewing the proposed Station layout for pedestrian movements (totalling about 7500 airport railway and 22 200 commuter passengers during peak hours), and for vehicular movements. Due to this dual function, the design called for different levels of service to be maintained and specific interchange requirements; Station design was undertaken to comply with the MTRC's stringent criteria. Passenger movements within the Station under normal and emergency evacuation scenarios were analysed, and advice given to the architects on Station design requirements.

All Hong Kong stations have to comply with very strict controls on safety and security, and also on links with other modes of public transport. Requirements are based on various government regulations but as each station's situation is unique the approval of these requirements is on a station-by-station basis, steered by the Station Transport Integration Committee and the Safety and Security Coordination Committee. Input by architect, M&E engineers, and transport engineers is obligatory and several submission stages are entailed until final approval is obtained. Arup's transport group provided the necessary skills to these processes.

Traffic engineering

Roadworks included external access roads and connections to the highway network, and internal Station access roads. As most of the vehicle servicing facilities were inside the Station, the internal road network surrounded the platforms and concourse areas on three levels and included requirements to accommodate 12m-long coaches.

Outside the Station the traffic team advised on the detailed road layout and undertook the detailed design of three traffic signal-controlled junctions. MTRC wanted to improve the appearance of the 'standard' traffic signage (without detracting from the Station's image), so the team was also commissioned to design the traffic signs and road markings, a task complicated by the need to comply with bylaws that were the subject of ongoing discussions between MTRC and the government's transport department.

Inside the building, facilities were provided for car parking, private coaches and limousines, and two drop-off kerbs for public use - each some 230m long, for both the AEL and TCL. The taxi facility planning included concepts for a control system to direct taxis to passenger pick-up bays. Although full facilities were not provided at day one of opening, the final design has 20 taxi pick-up bays catering for approximately 500 per hour, with queuing space for over 100 taxis within the Station.



Design and construction of the Station structure

In the event, the open-cut excavation method proposed by Arup was adopted by the main contractor, and brought advantages including:

- Construction was not reliant on a small number of diaphragm wall contractors who would be committed on many other Airport projects in the same construction period.
- Durability is a prime consideration in this aggressive environment, and in situ construction in open cut gave better quality control.
- Element planning is freed up, allowing structural freedom to use perimeter walls as deep beams and load distribution elements.
- Cost savings.

The other significant challenges on the project were recognised as:

- the high water table (at the ground surface under extreme conditions) and deep basements producing large uplift loads; the TCL bottom basement essentially becoming a 'moored ship' in the harbour
- waterproofing the structure under the high external water pressures, given the huge floor plate size and the degree of shrinkage restraint imposed by previously placed structure and massive pile caps
- additional bearing pressures on basement floors due to elastic and creep shortening of long piles under high column loads.

Structure

This reinforced concrete box incorporates three suspended levels above ground and two basement levels below ground, the latter housing four running tracks and platforms running north / south. The check-in and baggage-handling facilities are concentrated close to the centre of the Station on these levels and at ground level above, with plantrooms generally at either end of the Station away from the platform areas. Retail and commercial facilities are above the Station, so that they can be used by passengers en route to and from the railway.

Connection to the Station from other railway facilities is also possible, with provision for an underground pedestrian link from the nearby Kowloon-Canton Railway Corporation's proposed West Kowloon Station, and for the MTRC's own possible East Kowloon Line.

As already noted, the land above and around the Station itself is zoned for future commercial and residential development, and part of the railway works include foundations for these structures in the form of bored piles and pilecaps, with stub columns and couplers left for future connection by developers.

Foundations

A general geological profile after reclamation is described below:

Stratum	Thickness
Marine sand (fill and in situ)	18m - 30m
Left in place marine clay	Up to 6m
Alluvial deposits	0m - 10m
Completely decomposed granite	2m - 40m
Highly decomposed granite	2m - 40m
Moderately/slightly decomposed granite	

The future multi-storey developments necessitated high load capacities, and large diameter bored piles were found to be the most economical solution. Their number and size were varied to suit the loadings at particular points, both for efficiency and to provide foundations with similar load settlement characteristics to minimise differential settlement effects on the structure above. Diameters from 1m - 2.5m were used in groups of one to four piles per loading point.



7 above: Podium deck directly above Station box, with Station entrance beyond. Stub columns with couplers for future development can be seen in the foreground. The railway ventilation shafts are constructed to their final level so as not to cause disruption when more development decks are built around them.

8 left: Main entrance to station below steel roof, with long-span escalators and glass-clad lightwells.

This gave order, symmetry, and repetitive modularisation to the function and structure. The overall external form of the Station box itself was not an overriding issue, as most of the structure is below ground and that which is visible serves as a platform for future development.

The planning logic can be seen from the clear positioning of the major Station functions:

- TCL platform
- AEL platform
- Arrivals level, with large internal drop-off roads and in-town check-in for passengers and baggage
- Departures level with its associated transport functions: taxis, buses, mini buses, private car park, and internal departure pick-up road
- Station entry from the developments
- Service zones: extensive areas in each of the levels as required for their function.

The Station building grid was chosen from various studies undertaken by MTRC's concept study; this identified 12m x 12m as most appropriate for the diverse functions. Traffic management and the ability to turn MTRC's shuttle buses within this grid were essential. The structural design was dominated by the disparate requirements of the station box and need for a repetitive cost-effective construction using tried and tested methods.

9 below: Entrance roof detail from topmost deck level.



The piles vary in length from about 20m to a maximum of 106m where the rockhead slopes away into a fault zone. The 106m diameter long pile was believed to be the deepest bored pile in the world at the time. A total of 939 bored piles and 81 barrettes were installed for the Station box and tunnels.

Column loads vary significantly across the Station box, ranging from 17MN under the podium deck to 120MN under the future development blocks. From the outset of Arup's commission it was obvious that the sheer scale of foundations would be enormous, thus their cost would be a significant factor in the scheme's development.

As the Station supports future private (rather than governmental) developments, it is subject to the government's building ordinance and has to comply fully with local building regulations. For foundation design these are effectively prescriptive, and do not allow engineers to stray outside what is considered normal unless the particular foundation type or system can be demonstrated as complying with the regulations. In the case of Kowloon (and subsequently Tsing Yi Station) the many piles (over 1500 for the two projects) led MTRC and Arup to consider applying to the Building Authority (BA) for an enhancement of the maximum allowable pile carrying capacity. This was pursued in consultation with MTRC and the BA and a formal application was taken forward for a full-scale test regime for approval by the government. The tests were carried out on the Station site, fully instrumented and monitored by Arup and MTRC, and witnessed by the BA. The tests were required to satisfy the BA that the piles could satisfactorily carry the proposed loads both in compression and tension with a minimum safety factor of 2.

Arup's proposals aimed to enhance the bearing capacity by utilising the end-bearing value of piles founded in competent rock plus shaft friction developed in a rock socket. Compression loads are thus carried by this combination of end-bearing plus rock socket friction and tension loads purely by the rock socket. This resulted in rock sockets up to 7m in length for the contract piles.

The Kowloon test comprised two pre-contract piles each loaded with some 23MN of steel and concrete kentledge to provide the necessary reaction. As a result, up to 7.5MPa in end-bearing capacity plus a maximum value of 700kPa in rock socket friction was allowed. By adopting these values a cost saving in excess of HK\$200M (£16M) was achieved for the Corporation for Kowloon Station alone.

Contract piles were excavated within temporary steel casings by bucket and grab down to rock and then by reverse circulation drilling within the rock. In one area, the contractor elected to install barrettes as an alternative to the piles. These were installed using a rotary trench cutter machine under bentonite instead of the more usual clamshell method.

Basements

The Station box has a maximum depth of about 18m. Groundwater was lowered during excavation by a multiple wellpoint system around the perimeter, and the basements built bottom up using in situ concrete. The deepest has to resist a hydraulic head of about 15m of water under normal operating conditions. The base slab, between 700mm and 1.4m thick, was designed as a flat slab with thickenings at the columns / piles to resist shear where required. The piles were generally required to act in tension during construction until enough structure had been built above to put them into compression. The walls, generally 800mm thick, were designed as retaining walls, propped horizontally by the internal slabs and beams.

An area at the northern end of the Station was enclosed by a diaphragm wall about 150m long; here use of open cut was impossible, so it was constructed by the conventional clamshell technique under bentonite.

All elements were designed as water-retaining, with a secondary seepage collection system provided. For the walls this is a second inner blockwork wall with collection behind into a piped system, whilst for the base slab a proprietary cellular waterproof membrane was placed above it and below a thin secondary slab, above which the floor finishes were then installed. The cellular membrane is drained to a piped system.

Internal suspended structure

The main beams on grid are generally 1.5m wide and 700mm deep, with one 700mm x 700mm secondary beam at midspan in each direction. The columns vary in diameter from 900mm to 3m, depending on the development loading they are to carry. Rectangular or square columns generally are used in non-public and car parking areas, and circular columns in public spaces.

Slabs were designed as continuous two-way spanning wherever possible and vary from 170mm to 300mm deep, again depending on loading. The suspended structure is generally designed for four-hour fire resistance, and a secondary galvanised mesh is provided to the soffit of all of horizontal elements to prevent concrete spalling and exposure of the reinforcement during a fire.

Development loading

As already noted, the Station structure is designed to support future development above, with vertical loads taken down via the columns to the piles and pile caps, and lateral load carried by the moment frame action of the columns and beams. The horizontal members in the lateral frames are provided at every other floor to balance the distribution of moments between the beams and columns. Where the beams act as part of a moment frame, the depth is increased from 700mm to up to 2m to provide the required stiffness and capacity. The design allows for lateral loading from both wind and earthquake. Hong Kong being an area of low seismicity, no local code of practice was available, and as described in the article on Tsing Yi Station (pp38-43) Arup were commissioned to undertake a study. The outcome was to effectively adopt the draft New York code (NY has similar low seismicity), which uses an equivalent static method. With the height of the developments planned above the Station, and the typhoon wind loads for which all buildings in Hong Kong have to be designed, this was rarely a critical load case, as wind loading generally governs for highrise structures.

However, special reinforcement details such as additional shear reinforcement near joints and closed links in columns are used throughout the Station building to provide additional ductility in the event of an earthquake.

Structural steelwork

The central portion of the Station extends above to the final development podium level to allow access from the open air podium deck from future developments. Above this entrance, a long-span steel roof, curved in two directions, makes a visually striking feature, as well as giving large column-free voids beneath.

It is formed from two 1.5m deep curved plate girders spanning some 28m, between which 600mm deep castellated beams in turn support curved cold-formed purlins.

Castellated beams are used for both their low weight and to allow services and ventilation ducts to pass through the webs. Multi-layer stainless steel sheeting covers the space above, with large glass walls enclosing the sides.

The Station has many escalators, concentrated in the central areas - generally in large voids for a visually dynamic effect. As a result they span up to 36m, carried within deep U-frame trusses made of rolled structural steel hollow sections; space for maintenance access is included within the trusses.

Kowloon Ventilation Building

The KVB is at the southernmost end of the reclamation, and linked to the Station by the south cut-and-cover tunnels. Although relatively small, it has a prominent position, in response to which the architects designed one of the most visually striking services buildings imaginable.

The building will eventually sit within the future West Kowloon Regional Park and the architects decided that as well as performing its intended function it should enhance the park by being treated as a 'sculpted landscape'. Its appearance has been compared to various animal-like forms and appears to be ploughing its way through the current reclamation and towards the harbour. Terry Farrell's sketchbook states: 'The organic design - visually strong, but sympathetic to its setting - is based on an undulating form relating to both rolling landscape and the waves of the adjacent harbour.' The choice of black, grey, and yellow finishes adds to the building's unusual appearance.

10. KVB seen from Ocean Terminal, Tsim Sha Tsui.



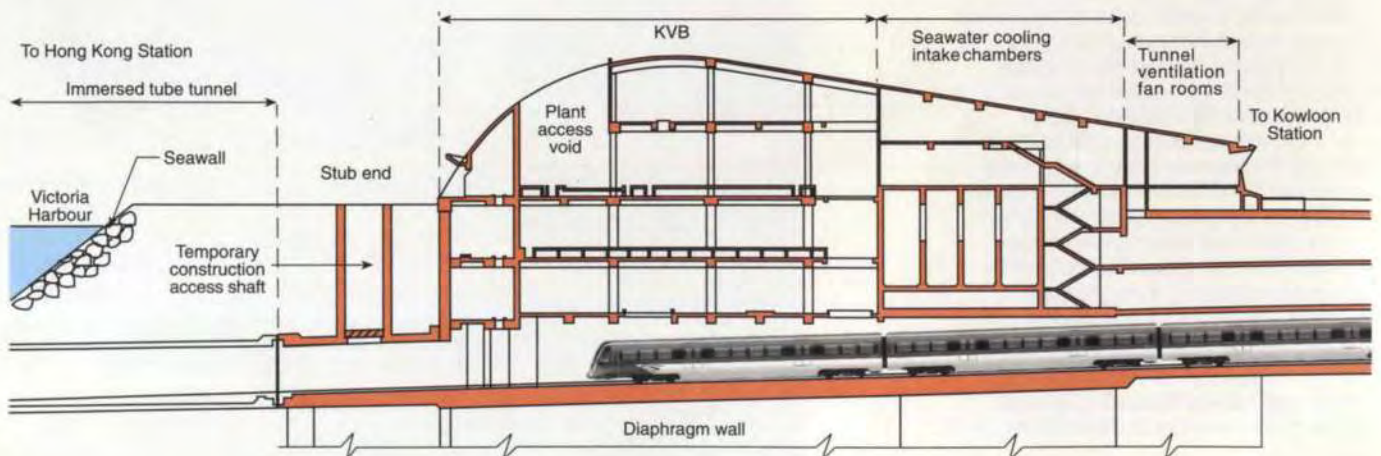


11.

KVB at sunset, seen from Western Elevated Road. The Peak Tower (another Farrell/Arup project) can be seen on the skyline.

12.

Long section through KVB.



The roof consists of arcs of three different radii, juxtaposed on which are five ventilation stacks with sloping and curved elements. To determine the correct geometry the above-ground part of the building had to be modelled in three dimensions, and this proved such a useful tool that Arup was able to give the architects guidance on the setting-out.

The KVB has a footprint of approximately 90m x 27m, rising some 20m above ground at its highest point, and contains five levels, three of them below ground. The lowest accommodates the AEL and TCL which merge to share just two tracks before they cross Victoria Harbour in MTRC's immersed tube tunnel. The structure is reinforced concrete with the below-ground section enclosed by 1.2m thick diaphragm walls, also serving as the foundation.

The ground conditions are generally 30m of marine sand fill overlying 0m-10m of alluvial deposits. The weathered bedrock was highly variable and was found 2m-40m in thickness. The excavation was approximately 85m long, 23m wide and 22m deep, and the foundations formed by taking alternate diaphragm wall panels down to bedrock.

The marine sand fill was vibro-compacted on the inside face of the excavation to increase the fill's passive resistance, and the resulting reduction of bending moments within the retaining wall gave a more cost-effective design.

The building was fast-tracked and complicated by the fact that two contractors were involved. The one for the cross-harbour tunnel had to build a small connecting piece named the 'stub-end', into which the immersed tube could be inserted. Once this was done, the KVB contractor completed the building and the south cut-and-cover tunnels.

Arup's scheme design of the building and co-ordination work were undertaken in Hong Kong, with detailed design done in Brisbane.

North and south cut-and-cover tunnels

South cut-and-cover tunnels

These are about 450m long, and run within the reclamation between the Station and KVB. They emerge from Kowloon Station 18.5m below ground level, rise by some 2.5m, and then drop down again to 21.5m deep at KVB. The tunnel box cross-section, which contains tunnels for the AEL and TCL up and down tracks, a refuge siding for AEL (AEL-RS), and a services tunnel, varies constantly throughout its length. It begins from Kowloon Station with a multi-cell box structure for four lines and converges to a five-cell box structure for two lines, before entering KVB.

Site conditions

The formation of this reclamation area was ongoing when the consultancy was awarded to Arup. It was soon decided to instruct the reclamation contractor to remove 15m-20m of the existing soft marine clay by dredging, and then place the marine sand fill over the relatively stiff alluvial deposit. This change allowed the tunnel structure to be designed as 'floating', ie ground-bearing, resulting in a saving of the piled foundations shown on the concept study proposals.

Analyses

Transversely, several typical cross-sections for the multi-cell box structure were considered for analysis purposes. They were designed as continuous and soil springs supports were modelled at close centres across the section. The spring stiffnesses were assessed from field measurements of the soil, and studies made on the sensitivity of the analysis to the stiffness values, to verify the design.

Longitudinally, the tunnel was idealised as a single line element and again supported on soil springs to simulate the ground beneath the base slab. Although the model was simple, the analysis was complicated by the need to examine the many construction and operation loadcases.

At the eastern end, provision had to be made to construct the possible future East Kowloon Line below the tunnels. To accommodate this a short length was supported on bored piles to enable it to span above any future works.

Construction

The tunnel's entire length was constructed in open-cut excavation. It was divided into four lengths, and each built from the middle out. The excavation was dewatered to 1m below formation, and the dewatering maintained until the final stages of construction and backfilling were complete along almost the full length. Backfilling of completed sections was maintained approximately 20m behind the workforce.

Temporary construction joints were provided at each end of the tunnel section. These 'stitching strips' were temporary waterproof movement joints to allow movement of the tunnels during construction. They were intended to be left as late as possible in the contract before concreting the joints, especially when connecting into a much stiffer structure such as the piled section of the tunnel at the north or the diaphragm wall of the KVB at the south.

The connections were then made after much of the tunnel movements had taken place. After this use of 'stitching strip' details, similar jointing details were also used for other LAR 'floating' tunnel structures mentioned in this Arup Journal.

The preliminary design of the tunnels was prepared in Hong Kong, with the detailed design done in the Manila office.

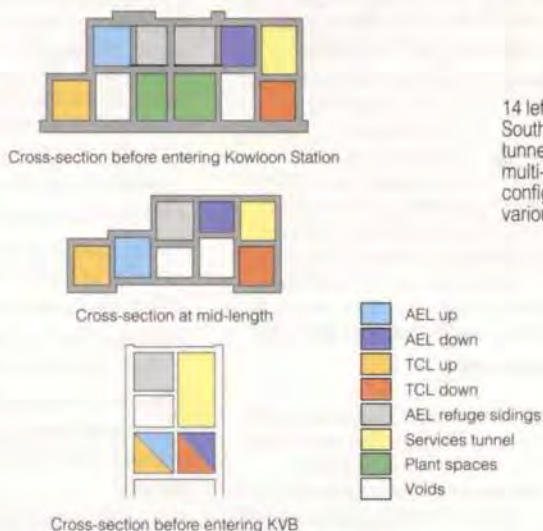
North cut-and-cover tunnels

These are immediately north of the Station's diaphragm wall. They are about 75m long and comprise four separate tunnels for the AEL and TCL tracks, connecting with the adjoining running tunnels taking the railway northwards to Olympic Station.

Again, they are of reinforced concrete, designed as a 'floating' structure, and were constructed in an open cut excavation.

A bulkhead was built at their interface with the Station box diaphragm wall, to await future connection; once the tunnels were complete, a highway structure embankment was built directly above them. Monitoring was carried out to confirm that settlement was substantially complete, prior to connection with the Station diaphragm wall.

13. South cut-and-cover tunnels connected to KVB. The extreme closeness of both tunnels and KVB to the harbour is evident.



14 left: South cut-and-cover tunnels cross-section: multi-cellular configuration at various locations.



15: South cut-and-cover tunnels, showing multi-cellular nature of box, with 'stitching strip' gap. The Station is beyond, on the left.

16.
Western
Elevated Road
and Road SR7.



Western Elevated Road and Road SR7

The WER and Road SR7 were part of the government's road system to complete the connection of the Station to the road system in West Kowloon as well as the West Kowloon Highway (WKH) and the Western Harbour Crossing (WHC). Construction was entrusted to MTRC by Government.

The WER and SR7 are vehicular access roads immediately west of the Station. Both are dual two-lane carriageways, the 500m long WER being elevated on supports from the central median of SR7. The WER serves the development above the Station via four T-junctions along its length, and SR7 the Station at-grade traffic. Roads D11 and D12, constructed by Highways Department, are further elevated roads connecting to the WER on the Station's northern and southern sides. Further west, and parallel to the WER, the WKH connects to the WHC.

The WER itself is a twin concrete box connected by diaphragms at the supports. One of its decks bifurcates to three decks to provide a slip road down to pass under Road D11, whilst an elevated 6m wide 'bus only lane', connecting to Road D11, passes between the WER's bifurcation and goes underneath it to connect to WKH and WHC.

The WER span lengths vary from 20m to 32m to suit site constraints, most of the decks being of cast in situ concrete with post-tensioning. For very short spans and at the T-junctions, reinforced concrete was used. The site geology was difficult, the rockhead dipping gently north / south from 39m to 46m below ground level for two-thirds of the bridges and then sharply down to 76m deep at the southern end. Bored piles were selected as the preferred foundation for most of the structure and barrettes where the rock is deeper than 66m.

Station development

The site

The West Kowloon reclamation, a large area of fill recently reclaimed from the sea to the west of the Kowloon Peninsula, has the Kowloon Station Comprehensive Development Area as its central and most significant part. The site is adjacent to the WHC toll plaza and bounded on all sides by roads.

The prime location on top of the Station is considered a great opportunity for commercial developments, extending the existing tourist, hotel, and commercial district of Tsim Sha Tsui so that Kowloon Station and its integrated property development will form the most significant transport hub on the Kowloon Peninsula.

The development

Arup's first involvement here was early in 1994, with the appointment by MTRC to advise Terry Farrell & Partners in the development of an overall masterplan. This involved structural and geotechnical advice on sizing vertical and horizontal structures, and the foundation design for the various tower blocks around the site. The proposed masterplan for the entire reclamation included a substantial mixed use development of retail, office, hotel, residential, and community facilities - to be carried out by the MTRC under a joint venture agreement - and consisted of a three-level podium over the whole site and approximately 30 towers around and above the Station. Due to height restrictions from the then existing Kai Tak Airport, these ranged from 30 to 38 storeys high and were to be a mixture of commercial, residential, and hotel blocks.

Since then the scheme has gone through several changes, the major one being triggered by the closure of Kai Tak and the removal of its height restrictions. The current masterplan design retains many of the fundamental design principles of the previous schemes, but has fewer, taller towers.

It is intended that the development be constructed in phased packages, and it has been divided into seven phases with the potential for separate ownership of each. The timing of each will relate to the payment of the land premium for each of the packages, which are as follows:

- First Development Package (residential / public bus terminus / GIC facilities)
- Northern Development Package (residential)
- South-East Development Package (hotel / residential / cross border bus terminus)
- Southern Development Package (residential)
- Station Development Package (retail, residential and hotel)
- Western Development Package (office and hotel)
- Landmark Development Package (hotel / office / retail)

Retail

Arranged on the first and second floors of the podium, this covers the southern half of the Station box. The retail layout also proposes a multiplex cinema. Natural lighting to the malls is a feature, from large areas of rooflighting arranged to contribute to landscaping the public open space at third floor level.

Office accommodation

This is in three towers: Tower 1 (Landmark Development Package), and Towers 20 & 21 (Western Development Package). The latter are a matching pair of commercial buildings, marking the Station entrance from the Harbour on the western edge of the Station box by being positioned symmetrically about the entrance's central east-west axis.

Their primary public entrance faces directly onto the central square, which has the Station entrance as its focus and is the commercial address for the scheme. The height of these towers is limited by the structural design of the Station and its foundations. Tower 1 is intended to be the landmark building for the development, the West Kowloon corridor, and Tsim Sha Tsui when viewed from Hong Kong Island and the Harbour. A luxury hotel is envisaged in its lower 30 floors.

Residential accommodation

The housing component is distributed across five of the seven Development Packages. The First has six residential towers, each 38 storeys above podium deck level. They are of a 'traditional Hong Kong style' eight-flats-per-floor arrangement, each averaging 90m². The Northern Package has five residential towers, and as they are not affected by the old airport height restrictions they extend to 52 storeys above podium level. Generally they are also in the traditional eight-flats-per-floor arrangement.

Landmark Tower

The Landmark Tower is the signature building in the masterplan design and provides an overall axial response to the Station concourse roof and entrance in the centre of the development.

As well as providing a strong visual identity to the development, it will also be a prestigious and valuable addition to the Kowloon skyline - which until now has been fairly uniform due to the Kai Tak height restriction.

From the beginning, MTRC strove to ensure that the Station development optimises the opportunities to create a balanced city quarter with a dramatic built form. MTRC have been steadily improving the built form and mix of uses for this development, to take advantage of the site's tremendous opportunities, and the revised planning parameters have allowed them to further revise the masterplan. Further analysis and refinement of the scheme design identified a balance of 12 000m² GFA that required relocation. This was intended for office and hotel use and could not be accommodated in other areas already committed. Being non-residential, it is most appropriately located in the main tower.

The original scheme tower had to accommodate a very high GFA with large commercial floor plates right to the top of the building. This would have given a uniform and bulky built form, and if it also had to accommodate the displaced GFA, it would have become even more massive and overbearing. MTRC, recognising the significance of the whole development to Hong Kong in terms of making a major contribution to the city's form and image into the new millennium, considered this building capable of further design development to the benefit of the overall urban design of the harbour and Kowloon areas. Accordingly, in January 1997 MTRC appointed the US architectural practice of Skidmore, Owings & Merrill, supported by Arup, to carry out further studies for a truly worthy Landmark Tower.

The result was a 480m design with a faceted glass wall, terminating with an architectural feature suitably substantial in proportion to the main part of the tower. The hotel bedrooms in the lower 30 floors surround an internal 120m high atrium, whilst the main restaurants and function rooms will be at the top to take advantage of the superb views of Hong Kong Island and the Kowloon Peninsula. The main entrance is one level above the podium and on the tower's south side to give arriving guests uninterrupted views of the Harbour. The entrance to the offices is on the north face with the main entrance from the podium.

A landmark must be interesting and also should well-proportioned to fulfil its role. This proposal will result in a true landmark, with the form and architectural quality of a truly eye-catching skyscraper rather than just another tall building in a city of tall buildings.

Generation of the tower form

The original scheme gave the tower vertical sides, maintaining floor plates at a constant, commercially acceptable size throughout its height. It was assumed that it would primarily accommodate office floors, with a hotel at the top, and that a standard plan form could be used with a structural building services core.

At the time of the approved masterplan in 1995 MTRC had only carried out a limited site investigation and the ground conditions in the area were not fully revealed. However, recent detailed site investigations have identified a significant geotechnical fault beneath the reclamation, and under the proposed tower. Due to commitments regarding the relationship of various other components of this complex development and the proximity of the railway alignment, the tower must remain at the same location and cannot be repositioned.

The proposed approach to overcome the problem is to span the fault, requiring the tower's primary structural elements to be at the perimeter of a large building footprint - too large to accommodate sensible and viable commercial floor plates in the lower part. This led to a tapered concept with progressively smaller floor plates, and it was decided that the office floors should be further up the building where floor plates would be commercially viable.

Thus the hotel will be in the lower part, which has two other significant benefits. Firstly, under typhoon conditions guests would have been sensitive to movement in the upper part of the tower, whereas office workers will be less sensitive, most being able to return home. Secondly, the proposed hotel is much larger and includes facilities such as ballrooms which are not practicable at the top.

Project organisation

The design of the project was broken down into various parts, and carried out in Arup offices both in Hong Kong and abroad. A central team in Hong Kong co-ordinated and managed the design process, the detailed reinforcement design and drawing being done by teams in Australia, the Philippines, and South Africa. Other elements such as the roadworks, the WER, and the civil design were undertaken by teams from the relevant groups in Hong Kong. Work carried out in Hong Kong included:

- liaison and co-ordination with the architect, services engineer, MTRC's design and site management, and other design teams working on system-wide railway elements
- sizing and preliminary design of all structural elements
- production of general arrangement drawings
- preparation and collation of government statutory submissions
- liaison with other disciplines and design teams
- monitoring of progress and liaison with out-of-Hong Kong detailed design teams.

Some structural analysis was performed in Hong Kong for particular elements where either speed was required and delay from using teams elsewhere was unacceptable, or where unnecessary duplication of the design effort would have resulted. This was adopted for the structural steelwork elements (eg glass lifts and Station roof), where design and co-ordination had to be closely linked.

Design work by teams outside Hong Kong included:

- detailed structural analysis both of structural frames and individual elements
- detailed calculations for government statutory submissions
- reinforcement detailing, including bar bending schedules
- design checks for particular elements of the design.

Conclusion

With the Station itself now functioning the emphasis is on progressing with development. MTRC continue updating the masterplanning at a detailed level by the design team, with a view to tendering further development packages in the near future following completion of joint venture deals for the first two packages in the last year or so.

The first development is currently on site with Arup providing the structural design role. The second package has been let and is under detailed design by others. Sitework for the Kowloon Station Square is under way. This comprises the first stage of the extensive landscaped podium deck directly above the Station which will provide outdoor leisure facilities for the future developments as well as giving access from them into the Station. Arup are also the structural engineers for this work.

Due to the South East Asian economic downturn it is not known when building the Landmark Tower will go ahead. However, given the ever-increasing pressure for land in Hong Kong its construction is inevitable at some stage. It will be a remarkable building that Hong Kong can be proud of.

Credits

Client:
MTRC

Architects, masterplanners and lead consultant:
Terry Farrell and Partners

Station

Civil and structural engineers and traffic & transport sub-consultant:
Ove Arup & Partners

Mechanical & electrical engineers:
Parsons Brinckerhoff (Asia) Ltd

Quantity surveyors:
Levett & Bailey

Authorised person & collaborating architects:
Ho & Partners

Main contractor (Kowloon Station, Western Elevated Road, SR7):
KEC Joint Venture (Kumagai-Gumi; Entrecanales; Cubiertas)

Main contractor (KVB, south cut-and-cover tunnels):
AMSOC Joint Venture (AMEC International Construction Ltd; Shui On Civil Contractors Ltd; China Fujian Corporation)

Main contractor (north cut-and-cover tunnels):
Aoki Corporation

Development and retail master planning / Kowloon Station Square

Civil and structural engineer and initial masterplan traffic and transport sub-consultant:
Ove Arup & Partners

Mechanical & electrical engineers:
Parsons Brinckerhoff (Asia) Ltd

Quantity surveyors:
Levett & Bailey
W T Partnership

Retail design collaborating architects:
Altoon + Porter Hong Kong Ltd
Chapman Taylor
Leigh & Orange Ltd

Landmark Tower study architect:
Skidmore, Owings & Merrill

Authorised person:
Kwan & Associates Architects Ltd

Landscape architects:
Aspinwall Clouston
EDAW earthasia Ltd

Main contractor (Kowloon Station Square):
China State Construction Engineering Corporation

Illustrations:

- 1: Martin Hall
- 2, 4, 5, 7-11, 13, 15, 16: Colin Wade
- 3: Terry Farrell and Partners
- 6: EDAW earthasia Ltd
- 12: Bird Wong / Jennifer Gunn
- 14: Emine Tolga / Jennifer Gunn
- 17: MTRC

17. Current masterplan with Landmark Tower proposal by SOM.



Hong Kong Station and Subway

Peter Brotherton

Background

Hong Kong Station is the final arrival point for visitors to Hong Kong itself, in particular for businessmen coming into the city and business district. Situated on 4ha of land reclaimed from the harbour, it holds a prime location.

Arup's involvement with what was to become the LAR's Hong Kong terminus goes back long before the new Airport and Railway were conceived. In early 1985 Hongkong Land Ltd were making final preparations to launch the first phase of their prestigious new office development known as Exchange Square (an Arup project). Three years earlier, at the height of a property boom, they had paid a world record price for the waterfront site in the heart of Central District and, despite a slump in the market the following year, held to their goal of a luxury development.

The first phase contained two 50-storey towers, one of the highest floors being designated as a show suite. A video was produced which included views taken during construction, and computer graphics were used to demonstrate the buildings' then high degree of intelligence. The closing aerial sequence showed Exchange Square itself and the wonderful harbour views it offered to its tenants.

What has all this to do with Hong Kong Station?

The video concluded with the phrase 'Exchange Square, the last waterfront site in Central', and typically for Hong Kong, that was to prove somewhat inaccurate. The new Station is located in the harbour directly in front of Exchange Square, and this was not to be the development's only link with it. Not only is Exchange Square immediately adjacent to the Station but it was to be connected to it by five footbridges, and a new Subway was to pass directly beneath it. The firm's knowledge of Exchange Square was probably a factor in Ove Arup & Partners being appointed as civil and structural engineer in December 1992. At the same time, Arup Associates were appointed as architects, in association with the local practice Rocco Design Partners.

Central District is Hong Kong's business hub. As well as the offices of all major banks and international companies, it houses the government's central offices and the former Governor's residence; given the pre-eminence of the location it was natural that MTRC should desire to make a 'statement' in developing the Station serving this most prestigious location on the new LAR. Central District has been extended around the new Station and its development, whilst the ferry piers to the outlying islands and Kowloon, connection to the existing MTR Island and Tsuen Wan lines, and the new road network have all contributed to the transport hub in the heart of Central District.

Central Station serves both the Tsuen Wan and Island Lines, and its main concourse lies beneath Des Voeux Road and World Wide House, a multi-storey office building developed by MTRC in the late 1970s. MTRC deemed it of paramount importance that the existing station be connected directly to the new. The railway being underground, it was natural that the preferred link be a dedicated Subway. In formulating proposals for submission to MTRC prior to being appointed, Arup considered that the Subway might have to be constructed as a bored tunnel, and appointed Charles Haswell & Partners as subconsultants for their expertise in this form of construction. However, ground conditions and other factors subsequently mitigated against this form of construction and cut-and-cover methods were adopted.

Contract UA11

The land essential for the project had to be reclaimed from the Harbour, but due to political issues a contractor was not appointed until 1 September 1993, some 12 months after the original date for work to commence. This put much pressure on the programme for the Station, whose opening was timed to coincide with that of the Airport. It was thus decided that a further contract to install part of the diaphragm walls and bored piles in advance of the main contract should be negotiated with the reclamation contractor. This was Contract UA11.

Because much of the reclaimed land would be occupied by the railway and its ancillary structures, the government had entrusted management of the reclamation contract to MTRC who were thus placed to negotiate a further contract with the contractor. Fortunately, the contractor could deploy additional resources for the diaphragm walls and bored piles, and only needed to re-sequence the production of the various areas of the reclamation for the additional works to commence; these consisted of 75 bored piles and some 590m of diaphragm wall.

The Subway contract was defined as finishing in Harbour View Street on the north side of Exchange Square, leaving just enough space to build an access shaft. The Station contract included all the works required to link the Station with the Subway on the opposite side of Harbour View Street.



1. The white area shows the site (almost entirely reclaimed land) before development, viewed from the east.



2. Site plan.

KEY

- 1 Hong Kong Station
- 2 Exchange Square
- 3 Ferry piers
- 4 Northern development site
- 5 Promenade
- 6 International Finance Centre
- 7 Underground chiller area
- 8 Subway
- 9 Bus station
- 10 New footbridge J
- 11 Temporary car park
- 12 Hong Kong ventilation building
- 13 Cooling water pumping station
- 14 Hong Kong power supply building
- 15 New footbridge C
- 16 New footbridge N
- 17 New footbridge O
- 18 New footbridge P
- 19 New footbridge Q
- 20 New footbridge X
- 21 New footbridge R
- 22 World Wide House and below-ground concourse for Central Station
- 23 Temporary footbridge
- Indicates extent of Station basement and tunnels

As part of the original government lease conditions for the Exchange Square site, HongKong Land had to provide a new bus terminus within their development to replace the existing one. All buses entered it by Harbour View Street, which had to remain open at all times. The contractor for the Station had not yet been appointed and even if he had, it was unlikely that he would be able to construct the connection across Harbour View Street for some time, given that the method of construction for the Station was to be top down. Much thought was given to how the final section of Subway from the Station site could be built without disrupting Harbour View Street's traffic. All forms of horizontal boring were ruled out, mainly because of obstructions in the form of H-piles supporting footbridges, and driven concrete piles carrying an elevated walkway.

If a feasible solution could not be found that did not require Harbour View Street to be diverted, it would be too late to divert it once Station construction commenced, so it was decided to implement further preliminary works in Harbour View Street under the UA11 contract.

A scheme was devised involving closure and partial demolition of the elevated walkway running the full length of Harbour View Street, together with two footbridges that connected the podium level of Exchange Square to it.

Following completion of preliminary works - demolition and diversion of the road - a diaphragm wall was installed to form the sides of a future chamber 38m long by 11m wide. A 1.3m thick slab (the future roof) was constructed, supported by the diaphragm wall, an upstand beam along its 39m long free edge, the H-piles previously supporting the footbridges, and some additional mini-piles. Where the diaphragm wall was omitted because of obstructions, the soil was grouted down to rockhead. Harbour View Street was returned to its former location after backfilling above the 1.3m slab and road reinstatement. Excavation of the chamber was eventually carried out by the Station contractor as part of his top down construction sequence.

Contract 501A: the Subway

Building the vital Subway between the existing Central Station and the new Airport Station presented some difficulties. The former was buried in the heart of Central District while the latter would be on new reclamation in the Harbour, and between them lay two major obstacles, the Pedder Street Underpass and Exchange Square.

The existing Station concourse is under World Wide House at the corner of the junction of Pedder Street and Connaught Road - one of the busiest in Hong Kong as Connaught Road is the main east/west route on Hong Kong island. Many services and utilities exist here including a large stormwater culvert: when the underpass was constructed, most of them had been diverted to the World Wide House side of Connaught Road. Because of its strategic importance to traffic flows in Central District, to close the junction and its access roads was impossible, though lane closures were acceptable. This necessitated a traffic management plan, approval of which by the Buildings and Highways and Transport Departments was necessary before the Subway contract could be let.

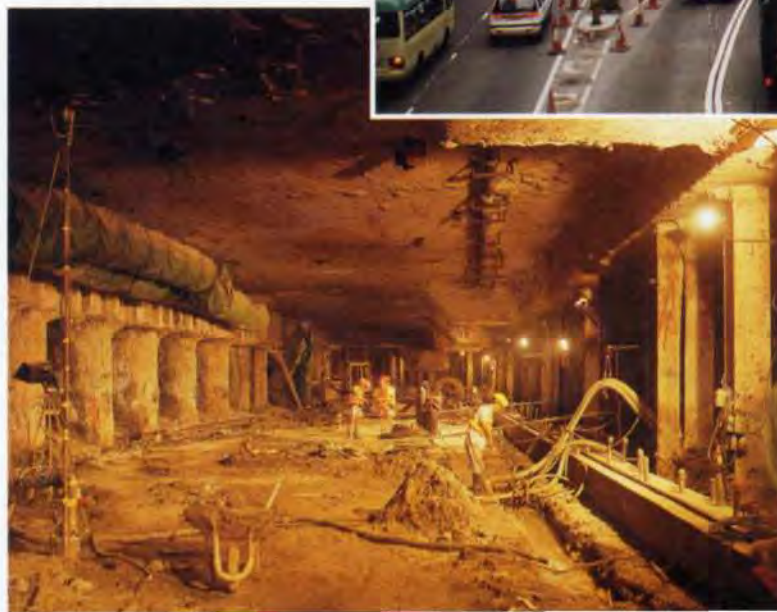
MTRC had recognised during the feasibility study that the Subway would be a difficult task and determined that most of its construction should form a separate contract from that of the Station, and be further divided into five zones, A-E. Zones A-D inclusive were to be built under contract 501A while Zone E in Harbour View Street was to be constructed as part of the main Station contract 501. This, in addition to Zone E and the Station building itself, embraced a chiller building, cut-and-cover tunnels, ventilation building, power building, seawater pipe tunnels, retail development structures, footbridges, and roads.



3. Construction from the west; centre: foundations of the International Finance Centre (South West Tower); behind: the Station buildings; right: Connaught Road Central.

4 right: View from north-west into Pedder Street Underpass.

5 below: Subway construction; left: exposed bored piles of Exchange Square towers; centre: exposed soffit of Exchange Square pile cap; right: exposed H-piles of Exchange Square podium.



Generally, the Subway was to be a concrete box or boxes within secant piled walls acting compositely with the box walls to resist soil and water pressure. In some locations, the difficulties were such that no common form of piling could be used, and the traditional Hong Kong method of hand dug caissons was employed.

The dimensions of the Subway vary depending on its location and proximity to existing structures. To maximise its width between the Pedder Street Underpass and the buildings on the south side of Connaught Road Central, it was necessary to demolish the canopies of several buildings for piling rigs to be placed close to them. At the junction of Connaught Road and Douglas Street, a further entrance / exit to the Subway has been provided, resulting in Douglas Street being permanently closed to traffic.

Zone D beneath Exchange Square presented special design and construction problems. The bus terminus occupies most of the site at ground level between the internal cores of Tower Two at the east end and Tower Three at the west end, whilst the podium above it acts as a transfer structure supporting a four-storey building.

Bus operation in the terminus required columns to be widely spaced east to west, generally 16m- 17m. In 1985 when most of the terminus was designed, H-piles founded in completely decomposed granite (CDG) was the preferred solution because of the depth to bedrock, some 60m below ground level. The configuration of the columns led to the design of continuous foundations running north / south, and it was between these foundations that Zone D of the Subway, consisting of two separate adits designed as floating boxes, is constructed. Some H-piles were located along the northern and southern Exchange Square boundaries. These were 'built in' during construction of the Subway and the section within the Subway subsequently cut out.

6.The Subway; in the background is a work commissioned for the location from Hong Kong artist Gaylord Chan by MTRC.



7. Main Station entrance for car / taxi / private bus drop-offs.





The design of the adits allowed for the transfer of vertical loads around them and back into the H-piles, effectively transferring additional load to the H-piles now supporting the Subway adits at their junction with the Exchange Square boundary. To counteract this, additional mini-piles were installed prior to casting the Subway base slab.

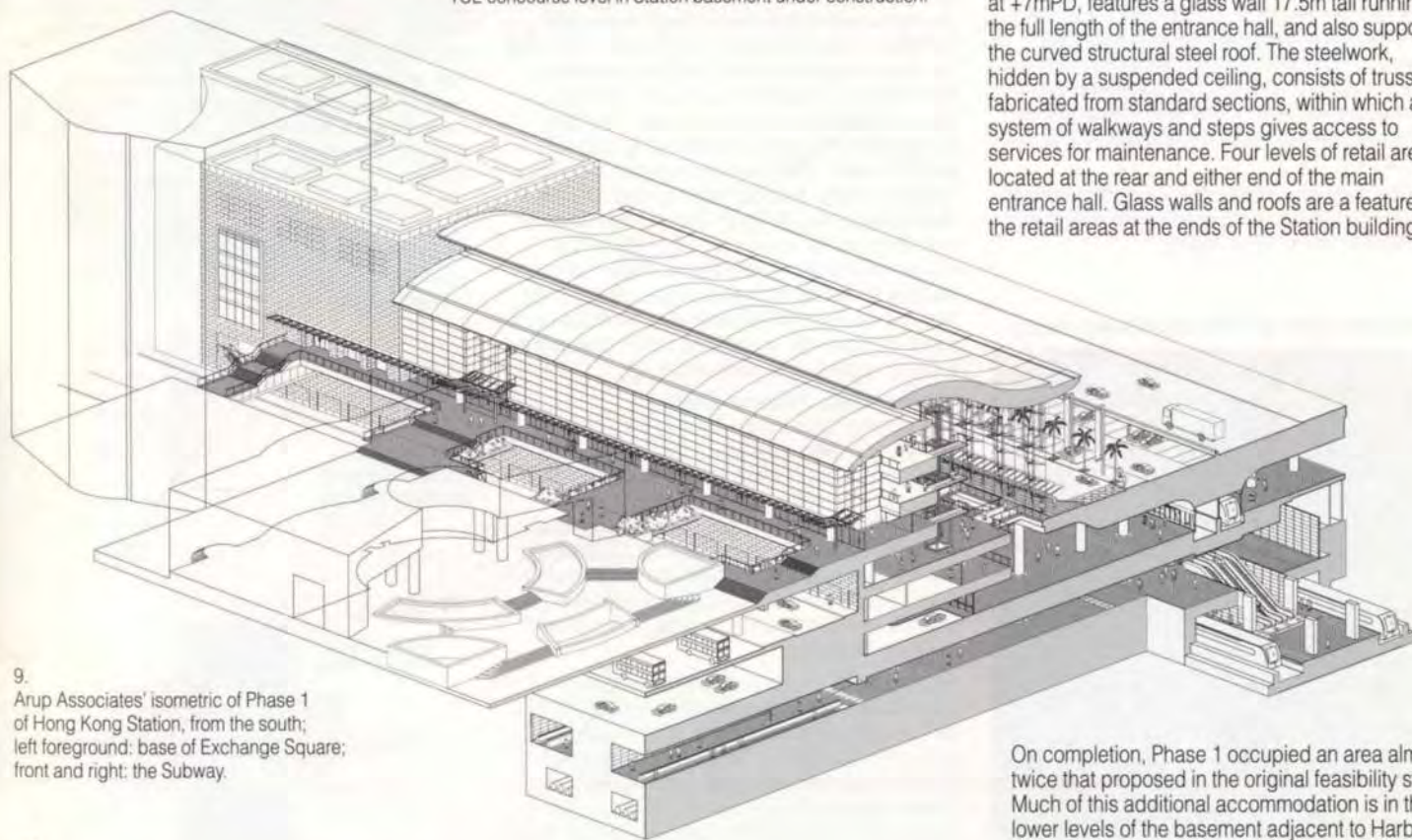
The Station: construction

The Station was to be built in two phases, Phase 1 basically containing Departures, ie in-town check-in, etc, and Phase 2 containing Arrivals and other major developments including retail. Phase 1 would also include all aspects of the railway operation plus a small amount of retail. At the time of opening, the Airport Express uses the same platform for both arrivals and departures. Phase 1 covers approximately 280m x 100m on plan, with four levels below ground.

The ground floor is at +7mPD, about 3m above the existing level of Harbour View Street; the top of the reclamation platform is level with existing ground level at +4mPD, necessitating the ground floor slab to be constructed on staging. Below this is the mezzanine level, housing most of the Station plant; below again is the Airport Express Level concourse (AEL), and then the Tung Chung Line Level concourse (TCL), to which the Subway from the existing Hong Kong Station is connected, and finally below that the Station is -16.725mPD.

8. TCL concourse level in Station basement under construction.

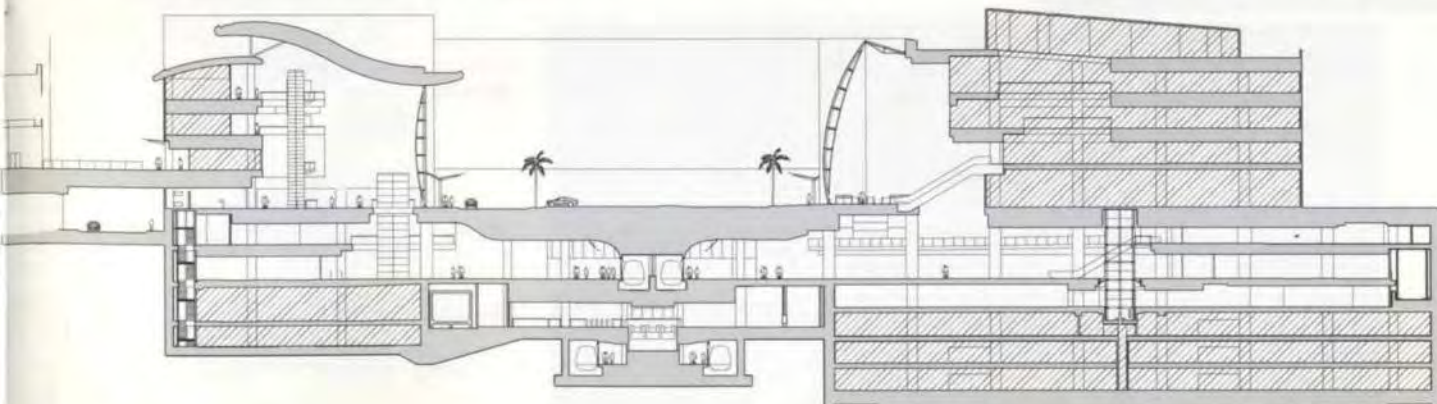
The main entrance, on the north side of the Station at +7mPD, features a glass wall 17.5m tall running the full length of the entrance hall, and also supports the curved structural steel roof. The steelwork, hidden by a suspended ceiling, consists of trusses fabricated from standard sections, within which a system of walkways and steps gives access to services for maintenance. Four levels of retail are located at the rear and either end of the main entrance hall. Glass walls and roofs are a feature of the retail areas at the ends of the Station building.



9. Arup Associates' isometric of Phase 1 of Hong Kong Station, from the south; left foreground: base of Exchange Square; front and right: the Subway.

On completion, Phase 1 occupied an area almost twice that proposed in the original feasibility study. Much of this additional accommodation is in the lower levels of the basement adjacent to Harbour View Street, and was a major factor in the decision to build the Station top down.

10. Cross-section: Phase 1 on left, as-yet-unbuilt Phase 2 on right.

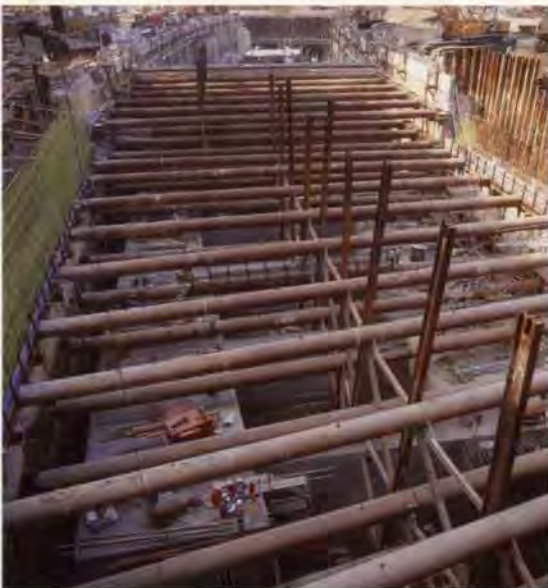


The Station box consists of diaphragm walls mostly 1.5m thick, varying in depth to rock from 30m - 70m; almost 50% of them are designed to support column loads as well as floor loading and the forces imposed by soil and water. Bored piles socketed into rock and barrettes founded in CDG provide support for internal columns. Because construction was to be top down, steel box stanchions fabricated from 60mm, 75mm, and 100mm thick steel plate were cast into the tops of both bored piles and barrettes, and were encased as construction progressed to form composite columns in the permanent structure. As at other stations on the LAR a 12m square grid was selected and costed as the most appropriate. Also in common with other stations, the main floor plates consist of main beams and single two-way spanning secondary beams with two-way spanning slabs for all levels except those cast on the ground, which are flat slabs.

As well as being the floor of the main hall, the ground floor slab also provides support for the external roads and lay-by areas. Because the utilities in the roads were to be adopted by the Drainage Services Department, and must be accessible from outside, they could not be dropped into the mezzanine level below. It was thus necessary to provide a 2m depth of soil between the road surface and the top of the Station box. This had two effects. Firstly, the headroom within the Station became very tight, the levels for roads and track being fixed and not alterable to any great degree. Secondly, it meant that the top slab had to contain sloping sections to achieve the difference in levels. It could not simply be stepped because of the large horizontal compressive forces it was designed to carry, and which could not be accommodated by additional bending moments in the columns.

To reduce the load on the steel stanchions during construction, loading on the ground floor slab was restricted to construction traffic.

11. Tunnels under construction showing temporary bracing.



Underground chiller building

Arup's initial scheme design put the chiller building at ground level, with the cut-and-cover tunnels - separate floating boxes constructed within a cofferdam - directly below. Many of the supports for the chiller building thus could not be taken directly down to foundation level, which necessitated the use of some large reinforced concrete beams spanning around 30m over the tunnels and onto the diaphragm walls forming the cofferdam. The roof of the chiller building provided the platform for a large landscaped deck which would eventually be connected to two hotels and be open to the general public.

However, it was subsequently confirmed that the site occupied by the chiller building would be required for an additional bus terminus. Several options were considered, the favoured solution was to accommodate all the chiller building functions within the cofferdam enclosing the tunnels. It also appeared to be the most cost-effective solution.

The accommodation below what was now to be a bus station in reality became an extension of the Station. The tunnels, which originally started at the Station perimeter, now commenced at the west end of the new underground chiller building. Slab levels within the chiller building had to follow the original line of the tracks, with the AEL tracks descending and the TCL tracks rising. The change in structural form also meant a change in construction method, with the top down method as used for the Station being adopted. This meant that the structural elements were also similar, ie diaphragm walls, barrettes, steel stanchions, and flat slabs. Planning the new underground chiller building was made more difficult by the differing requirements of the railway and the bus terminus above. The track configuration, including crossovers at both AEL and TCL levels, could not be changed, while the requirements for the bus terminus were for rows of columns on a 'regular' grid. The grid was 'regular' only as far as the unsymmetrical shape of the bus terminal building would allow. While most of the 30m span beams were no longer needed, the new arrangement still necessitated the inclusion of some large transfer beams and walls between the tracks to pass load to the foundations.

International Finance Centre

As its former name (South West Tower) implies, this is at the south west end of the Station. Under the Station contract it was to be part constructed up to roof level at the west end of the Station in order to complete the Station building envelope. The contract also required a transfer structure on which a future developer could construct an office tower. This was in fact built with its top level lower than the Station roof and a circular perimeter wall used to infill the gap.

Below ground, the structure had to include a ramp for taxis and mini coaches to access the AEL concourse level for departures and initially arrivals, plus a second ramp for the development car parking within the Station box. The access and egress points for the Station and development ramps also had to be located separately. With the limited site area available, this was achieved with two spiral ramps, one within the other.

The outer spiral ramp touched the site boundary on three sides so that, between them, the ramps occupied most of the site area for the tower leaving little useable space in the below-ground levels. It was therefore proposed that the outer wall should be constructed as a circular diaphragm wall, the advantage being that forces from soil and water pressure could be resisted by ring compression within the wall, making temporary propping unnecessary. This would allow the contractor to excavate within the diaphragm wall unhindered by obstructions. However, because of concerns over tolerances and the fact that a section of the wall was to be removed later, three horizontal ring beams were constructed as an added safety measure.

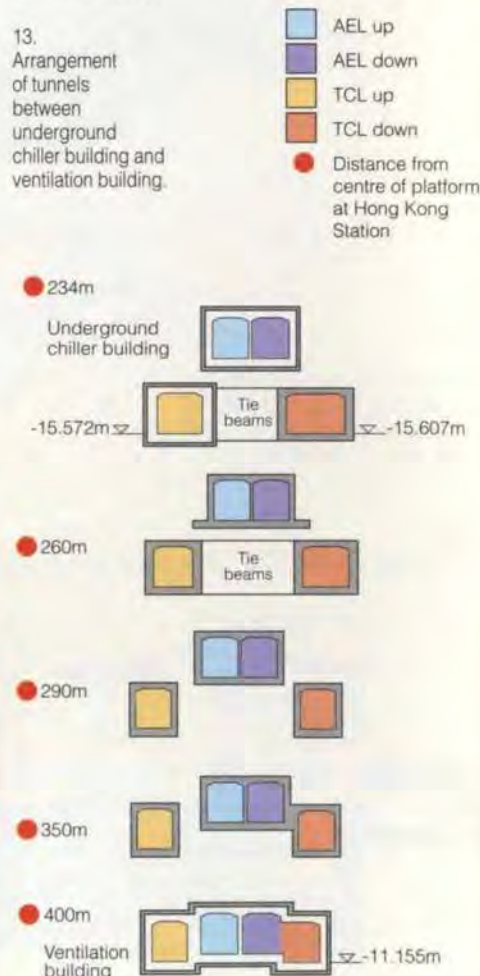
The tower is supported by the perimeter diaphragm wall and a pilecap at -12.5mPD, generally 3.5m thick, which transfers internal loads to 79 barrettes. The depth of diaphragm wall and barrettes varies but averages 79m. The International Finance Centre and the Station are separated by a movement joint sealed below ground by a *Jeena* gasket.

Cut-and-cover tunnels

The running tunnels extend for approximately 170m between the chiller building and the ventilation building. As they emerge from the western side of the latter, the four tracks - two outer AEL and two inner TCL - separate, enabling them all to reform at the underground chiller building but this time at different levels.

Because both the chiller building and the ventilation building are rigidly founded while the tunnels are 'floating', it was necessary to introduce temporary movement joints at each end of the tunnels. This was achieved by using a *Jeena* gasket to prevent water ingress while allowing the tunnels to move independently of the structures at either end. The joint was designed so that on completion of the works, the structures could be tied together. This was done after backfilling was complete and dewatering stopped to allow as much movement as possible before tracklaying. The tunnels generally have 800mm thick walls and roof with a 1m thick base.

13. Arrangement of tunnels between underground chiller building and ventilation building.



12.

Running tunnel immediately beyond the Station box.



Ventilation building

Mainly providing ventilation for the tunnels, this is close to the new sea wall at their western end. Its construction below ground was very similar to that of the chiller building in that it consists of diaphragm walls, barrettes with steel stanchions, and flat slabs wherever possible. It was also constructed top down. The basement has watertight doors which seal off the entrance to the cross-harbour tunnel to prevent flooding of the Station and its ancillary buildings. Above ground the structure occupies a much smaller site area due to the constraints of adjacent roads. The structure itself is mainly of reinforced concrete walls with some areas of beam and slab. A steel structure supports an external overhead travelling crane for lifting transformers.

Power building and seawater pipe tunnels

The power building started life as a small single-storey structure but grew to become a relatively large three-storey building including two basement levels. It is near the new ferry piers at the front of the reclamation and its form was to some extent dictated by its proximity to the proposed commercial developments above them. The two basement levels consist of a rectangular box about 47m x 12m, while the superstructure is an 'ellipse'. An elevated walkway - forming part of the system linking the piers to the Station and other areas of Central District - is supported on piers above the main roof to provide access for maintenance of the structure by Highways Department, as distinct from the power building itself which is maintained by MTRC. A steel and glass canopy covers the walkway, and adjacent to the power building a lift has been provided to give disabled access to the walkway. Apart from the steel canopy, the remainder of the structure is in reinforced concrete.

Both the new Hong Kong Station and the existing Central Station, and the future developments, will use seawater for cooling, and a dedicated tunnel was considered necessary for the pipes. The pipe tunnel joins the northern basement, constructed as part of the Phase 2 works, at its north west corner. To close off the tunnel and make it watertight, three panels of the Phase 2 diaphragm wall were installed under the 501 contract.

The seawater pipes were temporarily located in the ground from the tunnel to the underground chiller building pending completion of the northern basement. Reinforcement within the three diaphragm wall panels was arranged so that their structural integrity was maintained while making future breakthrough easier.

The volume of seawater used in cooling is quite large, making some means of disposal necessary, and a reinforced concrete culvert was built for this purpose. Constructed with both precast and in situ elements, it discharges directly into the sea through an opening specifically built into the new sea wall.

Footbridges

Seven footbridges link adjacent buildings to the new Station. Five of them cross Harbour View Street, connecting the Station to Exchange Square, and replace those originally connecting Exchange Square to the elevated walkway demolished during Station construction.

Only part of one of the original footbridges connecting Exchange Square Tower Two to the elevated walkway was retained and embodied in the new works. This was unavoidable as it formed part of the means of fire escape from the Stock Exchange within Tower Two and it was essential that it continued to fulfil this function during reconstruction. Reconstruction included the provision of a new permanent concrete staircase linking the footbridge directly to Harbour View Street.

A new footbridge at the east end of the Station connects with Hong Kong's main Post Office in addition to the major elevated walkway connecting the ferry piers with the main business area in Central District.

At the west end, pedestrians using the elevated walkway along Connaught Road Central now pass through the International Finance Centre building.

The original line of this walkway had to be diverted because its existing supports encroached onto the line of a new road underpass. Also connecting to the International Finance Centre is a new footbridge which presently links to a temporary elevated walkway connecting to the ferry piers.



In town check-



14.

AEL concourse.





15.
Main Station entrance by night.

16.
Concourse hall, showing hanging sculpture, commissioned by MTRC, by Larry Kirkland.



This temporary walkway will be replaced when the bus terminus above the underground chiller building is completed and the space becomes an open public area linked to the hotel development.

Widths of the footbridges vary: three are 12.0m wide with 2.5m wide cantilever planters down each side - 17m in total. All five crossing Harbour View Street consist of precast beams with an in situ concrete topping slab, while those at the east and west ends are entirely of in situ concrete.

Geotechnics and foundations

Foundations follow the general pattern for large buildings with deep basements in Hong Kong. Flotation is an issue for all such buildings, making it essential for each type of foundation to be able to support compressive loads during top down construction, and tension loads following completion of construction when groundwater levels return to ambient. To check the assumptions made when designing for these requirements, two bored piles and one barrette were successfully tested. Rockhead shelves steeply across the site east to west, and further west rockhead was not found. As a result, bored piles were used for most of the Station with barrettes becoming more practical and economic when rockhead reached 65-70m below ground. Hence, barrettes were used at the west end of the Station, for the International Finance Centre, the underground chiller building, and the ventilation building.

Monitoring the settlement of Exchange Square was a complex task, involving at one stage three separate contractors all working in close proximity, or in the case of the Subway underneath the building itself. Further complications arose with construction of the Subway immediately adjacent to buildings along Connaught Road. Consequently, there was a need for geotechnical monitoring and input throughout the whole of the project.

Other areas where geotechnical considerations played a major role in the project were:

- prediction of future movement of the Phase 1 Station box during construction of the adjacent deeper basement for Phase 2 of the Station and development car parks.
- prediction of future movement of the underground chiller building and running tunnels during construction of the adjacent deeper basement for the hotels
- checking stability of the circular diaphragm wall in which the South West Tower basement is constructed
- surcharging of the fill by dewatering prior to construction of the cut-and-cover tunnels to limit settlement.

The first two items had to be considered in the light of the maximum 20mm movement in any direction allowed under the present Building (Construction) Regulations in relation to MTRC structures.

The Station box is basically a 280m long sway frame in that there are no shear walls except for one short reinforced wall approximately at its mid-point. To establish a 'figure' for the expected maximum movement due to future excavation of the adjacent development basement it was necessary to do a great deal of analysis using FREW and GSA programs. From these investigations it was decided to install an additional diaphragm wall connected to the base slab running north to south at the mid-point of the Station box, and make provision for future dewatering below the new Station to reduce the tension forces at the slab/diaphragm wall connection acting between Phases 1 and 2. The maximum force developed in the AEL Concourse slab at -3mPD due to soil and water pressure was 2000kN/m.

Problems relating to the underground chiller building and running tunnels were similar to those of the Station in the need to restrict movement of the structure during excavation and dewatering of the adjacent basement.

Architectural planning

Arup Associates

Introduction

Arup Associates was successful in bidding for the architectural design of this flagship station - the only one on the new line to be built in an existing commercial area - against strong international competition. An association with Rocco Design Partners, who provided the local knowledge and expertise in Government procedures, was formed and a project office set up in Hong Kong. Work on the detailed design began in December 1992.

Design and construction of the project was to be undertaken in two phases. Phase 1 was completed in June 1998, with construction of Phase 2 not due to begin until late 2001 with completion in 2003.

The project

Hong Kong Station is effectively two stations, one on top of the other with a concourse in between, all below ground level. The 'lower' station serves the Tung Chung Line whilst the Airport Express Line terminates at the 'upper' station; this will ultimately be provided with separate arrivals and departures concourses.

The brief also included the design of ground level works around the Station - including a baggage check-in facility for the Airport - the ancillary buildings, and the central Subway. The strategic planning of 415 900m² of associated commercial development, comprising three office towers, retail malls and luxury hotels, was later added to Arup Associates' brief.

MTRC's objectives and the brief for Hong Kong Station were derived from the aims for the whole LAR scheme. These can be summarised as:

- to provide a new railway designed to the best modern standards of safety, performance and quality, and to facilitate the rapid transportation of the large number of people who are expected to use it
- to construct the project as economically as possible
- to construct and operate the LAR with minimum disturbance to local communities and the environment
- to optimise the site value generated by developing suitable property in association with the railway facilities

To achieve a level of consistency in the four LAR stations, the client gave each architect several further aims:

- an attractive overall design which encourages patronage
- optimum exploitation of natural lighting
- introduction of multi-volume space
- clarity of orientation and circulation
- efficient and effective circulation within the station public areas and the links to surrounding developments
- use of high quality finishes with an emphasis on crispness and precision
- durability and ease of maintenance
- safety.

Architectural character

Light and orientation were the two key themes of the design. Since the Station development is predominantly underground it was important to avoid the feeling of a 'rabbit warren'. Further, the new Station - and particularly the AEL - was to echo the atmosphere of an airport terminal, so that passengers feel they are using a shuttle rather than a separate railway. The two new LAR lines which terminate at Hong Kong Station, therefore, share a common design language which takes its cue from the Airport Terminal buildings.

This is particularly so in the Airport Express Station where the large volume of the main check-in hall with its fully glazed north wall (the largest in Asia) and generous light-wells is fully exploited to bring natural daylight deep into the heart of the station concourse below. The wave-form ceiling in the AEL concourse is designed to draw passengers naturally towards the daylight, thereby helping to orientate them in their surroundings.

The widespread use of granite floors and wall surfaces, combined with the use of system-wide design components such as signage, telephones, glass lifts, seats, etc, provides a consistent unifying character to all the new stations. The sharply detailed, well-lit, and uncluttered appearance contrasts strongly with the large expanses of coloured mosaic tiles and dark ceilings used in the older MTR lines.

The limited palette of cool grey and white surfaces with occasional splashes of MTR dark blue is intended to create a sophisticated feel, the effect of which is immediately calming as one walks from Central Station into the new Subway to Hong Kong Station.

The urban planning concept was to relate the end blocks of the Station to the podium of Exchange Square which has no windows. Bridges to the Station also link up with all the north-south public routes at ground level of Exchange Square.

Central Subway

The connection of the new Station to the existing MTR lines at Central Station was a critical part of the Airport Railway infrastructure and formed a significant part of the overall project. The routing and planning of the Subway was added to Arup Associates' role. The interface with the existing operational railway station required a number of detailed and complex design studies, involving the integration of significant inputs from various parts of the client body.



19 above:
In-town check-in hall.



17 above:
Customer Service Centre, designed by Arup Associates.

20 below:
Lift from AEL concourse to check-in hall.



18.
The Subway.





21. Steelwork detail in check-in hall.

22 below:
Light-well viewed from
AEL concourse into check-in hall.



Construction

The Subway contract was let in December 1994 and a completion date of March 1998 set. For the contractor, construction of the Subway presented a major challenge in that virtually the whole of the works had to be completed while maintaining vehicle and pedestrian flows at one of the busiest road intersections on Hong Kong Island. In addition, he had to thread two sections of it between the piled foundations below the Exchange Square basement. That he did so, and still achieved a high standard of finish and completed the works on schedule, is greatly to his credit.

While the Subway contractor had some problems with site possession (given the location this was not unexpected), his main problem was where to start. For the Station contractor, the situation was entirely the opposite, in that there was little that he could do following award of the contract in mid-June 1995. It was to be some six months later, between Christmas and New Year, before the first section of concrete slab at ground level was poured. This was due for the most part to the initial delay in commencing reclamation. Arup's Cardiff office was commissioned by the Station contractor for the detailed design of the steelwork.

Unlike the Subway, the Station was more a question of producing a very large quantity of work in a very short period of time. This is not to say however, that the Station and its accompanying structures were not without problems. The organisation of the many diverse contracts required to produce a fully operational railway was a daunting task.

A look at the statistics give some idea of the scale of the work:

- overall length of diaphragm wall 1300m (on plan), up to 70m deep in parts
- 275 bored piles and barrettes: bored piles up to 2.2m in diameter and barrettes ranging in size from 1.5m x 2.8m to 1.5m x 6m.
- approximately 745 000m³ of soil excavated and disposed of
- approximately 225 000m³ of concrete used with a peak of 6830m³ in one week
- the largest single concrete pour ever in Hong Kong: 72 hours
- contract completion date 21 June 1998, just three years after award of contract.

Credits

Client:

MTRC

Architect:

Arup Associates

in association with Rocco Design Partners

Civil and structural engineer:

Ove Arup & Partners

Subway sub-consultant:

Charles Haswell (Far East) Ltd

M & E engineer:

Meinhardt (M&E) Ltd

Quantity surveyor:

Davis Langdon & Seah (Hong Kong) Ltd

Main contractor (Station):

Aoki Corporation

Main contractor (Subway):

Kier / Sun Fook Kong Joint Venture

Main contractor (reclamation):

Dragages - Penta - Bachy Joint Venture

Illustrations:

1: © MTRC

2, 13: Jennifer Gunn.

3, 5-8, 11, 12, 16, 18, 19, 21: Colin Wade

4: Beth Morgan

9, 10, 20, 22: Arup Associates

14, 15, 17: Gareth Jones

George Acuna
Dan Adoriso
Leo Aguiar
Nima Alborz
Roger Alley
Andrew Allsop
Graham Annandaie
Nick Antonio
Ross Argent
Bruce Arthur
Henry Arundel
David Ashurst
Kitty Au
Kwok Chung Au
Tony Au
Wing-Hoi Au
Danny Au-Yeung
Peter Ayres
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Ian Burton
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Paul Callum
Rona Calvelo
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Richard Cowell
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Wilma Cruz
Graeme Curnick
Jo Da Silva
Pat Dallard
Jim Daly
Philip Dauncey
Andrew Davidson
John Davies
Duleep de Silva
Alex Dekker
Neil Dely
Richard Denham
Rob Devey
Jim Donaghue
John Duncan
Paul Dunne
David Edwards
Kate Edwards
Jeffrey Elliot
Mike Evans
Belzazar Fajutagana
David Ferguson
Oliver Fitz-Henry
Kieran Flynn
Andy Foster
David Fox
Matthew Free
Suzanne Freed
K Fung
Lawrence Fung
T O Fung
Clive Gaitt
Andrew Gardiner
Jane Gardner
Rolly Gatus
Graham Gedge
Chris Georghiou
Craig Gibbons
Andre Gibbs
Chris Gildersleeve
Clive Gillam
Graham Goymour
Dawn Grady
John Grant
Lee-Zane Greyling
Kim Gutteridge
Reynaldo de Guzman
Howard Gwatin
Tim Hackett
David Hadden
Robert Hale
Tracy Ann Hall
Don Hammond
Peter Handley
Mike Harley
Andrew Harrison
Martyn Harrold
Roger Hayim
John Hayman
Julian Hill
Lucy Hirst
Albert Ho
Jack Ho
Sai Lung Ho
Stanley Ho
Wilson Ho
Clive Holman
Dominic Holt
Ian Hooper
Steve Hope
Alastair Hughes
Kennis Hui
Lawrence Hui
Shirley Hui
Rex Humphreys
Stuart Hunter
Naeem Hussain
Roger Hyde
Tommy Ip
Carla James
Paul Jansen
Deepak Jayaram
Ian Jones
Isao Kanayama

Chris Karwoski
David Kaye
Simon Kemp
Neil Kendrick
Gavin Kerr
Simon Keung
Chris Kler
Martin Kirk
Bob Knight
John Knighton
Andre Kocmierowski
Julius Kovacs
Di-Yung Kwan
Samuel Kwan
Michael Kwok
Nelson Kwong
David Lai
Kelvin Lai
Tracy Lai
David Laing
Ben Lam
Pleny Lam
Winky Lam
Tony Langford
Ana Lanin
Tom Larmour
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Charles Law
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CK Lee
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Grace Lee
Keith Lee
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Philip Lee
Peter Lees
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K H Leung
Koon-Yu Leung
Leonard Leung
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Winnie Leung
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Ronald Li
Matthew Lilley
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Andy Liu
Anna Liu

Simon Liu
Ka-Leung Lo
Stewart Long
Joseph Lor
James Lui
Pierre Lui
Wing Yan Lui
John Lucas
Steven Luke
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Front cover:
Chek Lap Kok island, showing Hong Kong International Airport and the Ground Transportation Centre in the foreground, and, in the distance, HACTL SuperTerminal 1 (centre) and Tung Chung new town (left) (Photo: Pacific Century Publishers / Airphoto International Ltd. e-mail: airman@gateway.net.hk)

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(Photo: Colin Wade)

Back cover:
Main check-in hall, Hong Kong Station (Photo: Colin Wade)

Inside front cover:
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