ARUP 60TH ANNIVERSARY YEAR

KCRC WEST RAIL SPECIAL ISSUE

The Arup Journal

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Contents

Foreword

For 20 years the Kowloon-Canton Railway Corporation has been a significant client for Arup in Hong Kong. This period has seen a substantial growth of the KCRC's railway network to meet the needs of an expanding population in Hong Kong, and rapidly developing domestic and inter-city services with major cities in mainland China.

As the first railway company in Hong Kong, opening in 1910, the KCRC operated domestic, cross-boundary and inter-city railway services for most of the 20th century on what is now known as East Rail. However, the KCRC in its role as a public corporation has become a planner, designer and builder of major new railway networks, in response to Hong Kong's development.

Since 2003, new lines have been added to the network with the initial phase of West Rail, which is covered in this special issue of *The Arup Journal*, followed in 2004 by the extensions for East Rail on Ma On Shan Rail and the Tsim Sha Tsui Extension. Our projects for these lines, together with our involvement in the Lok Ma Chau Spur Line, will be covered in a further special issue of *The Arup Journal*.

Arup has played a very significant role in the design and provision of many specialist inputs as well as construction supervision in all of these projects, and I am pleased that this special issue has been devoted to recording our achievements on West Rail.

Andrew Chan
Chairman, Arup East Asia Region

Arup and the Kowloon-Canton Railway

Grant Robertson

1. The Kowloon-Canton Railway, circa 1915.

> **"Their [Arup's] design excellence has enabled the development of a unique track form and viaduct design, resulting in an approach to noise and vibration control which is expected to set a world standard for the acoustic performance of urban passenger heavy-rail operations."**

James Blake, formerly Senior Director,
Capital Projects, KCRC

Introduction

In 1863 plans were proposed to link Peking (now Beijing), Tientsin, Shanghai, Hankow, and Canton (now Guangzhou) by a rail network. Routes to India and to Kowloon in Hong Kong were also put forward, but the Imperial Government in Peking was not enthusiastic. With commercial interests in Hong Kong seeking to open up southern areas of China for trade, however, the idea of a rail link re-emerged in the 1890s and an agreement was signed in 1899 between the Imperial Chinese Railway Administration, Jardine Matheson and Co, and the Hong Kong and Shanghai Banking Corporation, "for the construction and working of railways from Canton to British Kowloon". After further negotiations and survey work, construction of the initial routes began in spring 1906.

The 36.2km British section of the railway included 48 bridges, 66 culverts, and five tunnels (Beacon Hill Tunnel was 2.2km and the longest in China at the time). Initially there were four stations, but the terminus at Kowloon and two other stations were soon to be added. The railway opened on 1 October 1910, and since then this line, now East Rail, has been the backbone of Hong Kong's rail network.

Over the years the line was modernized, double-tracked, and electrified, and by the mid-1980s expansion of the depot facilities at Ho Tung Lau, Shatin, was essential to maintain and stable new rolling stock to nearly double the fleet size. Redeveloping the depot at Ho Tung Lau was the first new railway project for which KCRC commissioned Arup, as well as the first where KCRC was required to manage its designers and ensure co-ordination within its operating departments. KCRC and Arup worked together to set up the appropriate design management structure for the project.

At about the same time, KCRC commissioned a design-and-build turnkey project for a new light rail transit system between Tuen Mun and Yuen Long in the North West New Territories (NWNT). Again, Arup played a key role as designer of all the civil, structural, and MEP work for the consortium contracted to deliver this new system.

The growth of the new towns of Tuen Mun, Tin Shui Wai, and Yuen Long was now well under way and by the early 1990s there was a clear need for rail links into the business areas of Kowloon from the NWNT. Concurrently, population growth in the eastern part of the territory around Shatin and the Ma On Shan areas also pointed to expansion of KCRC East Rail. Early planning work and feasibility studies were carried out for two new lines – West Rail and Ma On Shan Line.

West Rail

West Rail was planned to link Tuen Mun, Tin Shui Wai, and Yuen Long in the NWNT with Tsuen Wan, Sham Shui Po, and East Tsim Sha Tsui on the Kowloon peninsula. Phase 1, between Tuen Mun and Sham Shui Po, is 30.5km of twin track railway at grade, in tunnel and on viaduct. There are nine stations with an interchange to the Mass Transit Railway (MTR) lines at Mei Foo to the Tsuen Wan Line, and at Nam Cheong to the Tung Chung Line. Yuen Long, Tin Shui Wai, Siu Hong, and Tuen Mun all have interchanges with the light rail network.

Phase 2 will eventually connect Nam Cheong Station to East Tsim Sha Tsui Station. This extension – the Kowloon Southern Link – is now being built as three design-and-build contracts.

Arup was awarded one of the seven main detailed design consultancy packages - the Yuen Long Section - and was subconsultant on the Tsuen Wan Section for the detailed design of Tsuen Wan West Station. The firm was also appointed as independent checking engineer for the two tunnel packages – the Kwai Tsing Tunnels, which used a mixture of drill-and-blast, cut-and-cover techniques, and large diameter tunnel boring machine (TBM) in mixed ground, and the Tai Lam Tunnel, using the drill-and-blast method through rock. Before construction, Arup was also awarded a consultancy to design and supervise a large-scale pile test programme for the whole line. The aim of this was to obtain agreement from the Hong Kong Building Authority to accept higher pile capacities than were currently being used and thus gain cost savings for the significant amount of piling needed for the railway.

The Yuen Long Section, the largest consultancy package, comprises three elevated stations at Yuen Long, Long Ping and Tin Shui Wai, and 7.6km of viaduct. The concept design for the latter was then adopted for all viaduct structures. The acoustics and vibration design for the viaducts and the stations was particularly noteworthy.

Other Arup services

Arup's specialist capabilities in noise and vibration and environmental assessment have been vital to the complete engineering designs of these projects. Several of the station designs allow for the integration of associated developments, a solution to help railway operators cover part of their capital cost investments with property or commercial sales or rental income.

Conclusion

Arup's commitment to these KCRC West Rail projects has been extensive. The detailed design commissions resulted in six separate construction contracts, and Arup had to source resident site teams to supervise all of them. This required a total site staff of more than 230 over the construction period of nearly five years.

The firm's work with KCRC has not been confined to West Rail. Arup has also had major involvement in the Ma On Shan line and other significant aspects of the East Rail extensions. A second special issue of *The Arup Journal* about these is in preparation.

2. Part of the West Rail viaduct at Au Tau.

3. Outline map of the KCRC West Rail and East Rail lines.

Grant Robertson is a Director of Arup in Hong Kong. He has been responsible for the early railway work, particularly the Light Rail and Ho Tung Lau maintenance centre projects. He was the Project Director for the Yuen Long Section and took the role of The Engineer.

West Rail: an introduction

Colin Wade

As a result of the Hong Kong Government's new town programme begun in the mid-1960s, the original Tuen Mun village and later (when new housing targets were introduced in 1972) the market town of Yuen Long, some 40km by road from urban Kowloon, were both earmarked for major expansions. However, these two areas in the NWNT had no rail link into Kowloon or Hong Kong Island.

The light rail system between the two centres was originally conceived in 1972 when they were small communities, and when eventually opened in 1988 did not connect to the urban rail system. As the towns grew, commuters to Kowloon and Hong Kong were forced to use road transport for their entire journey or travel to the nearest MTR station at Tsuen Wan some 22km from Yuen Long - still some 13km by rail from the Tsim Sha Tsui district. Thus a fast, efficient, and less-polluting public transport link to the NWNT was considered by the Government's Second Comprehensive Transport Study (CTS-2) to be a priority along with two other rail projects. However, following the Government's 1989 decision to build the New Airport Railway, the timing and priority of projects recommended in CTS-2 had to be reassessed, along with the increased economic interaction between China and what was still the colony of Hong Kong, future cross-border freight, and rail passenger requirements.

Against this background, the Government commissioned consultants to carry out the Railway Development Study (RDS), which assessed over 90 railway schemes, and in December 1994 it published the result. The overall network would comprise two strategic rail corridors, an enhanced easterly one using the existing KCRC line (East Rail) as a backbone and a new western corridor through the NWNT. Thus was born the Western Corridor Railway (WCR), as it was initially named.

In January 1995 the Transport Branch of the Government Secretariat invited KCRC to submit proposals for building and operating the WCR. After a detailed feasibility study, KCRC made a full proposal to Government in November 1995. KCRC committed itself to provide the entire project as laid down in the RDS, including a cross-border service, a freight service to the existing container port in Kwai Chung, and the sub-regional (commuter) service to terminate at West Kowloon. However, due to financing and the need to initiate the more urgently required sub-regional passenger service, it was agreed that the railway would initially be built from a terminus at Tuen Mun town centre to an "upper" terminus at Sham Shui Po district on the West Kowloon peninsula, with seven intermediate stations. The freight, cross-border service, and extension to a proposed large-scale domestic and cross-border station at West Kowloon nearer to the Tsim Sha Tsui tourist areas would be deferred, studied further, and possibly phased.

Technical studies for what became West Rail ran from late 1996 to the end of 1998. Detailed design began late in 1997 and extended to mid-1999, while construction took just over five years, from autumn 1998 to the end of 2003, with revenue operation commencing on 20 December.

General statistics

Alignment characteristics	
Viaduct	13.4km
Bored tunnel (TBM or drill-and-blast)	9.0km
Enclosed structure-at-grade	3.2km
Cut-and-cover tunnel	2.5km
Open surface alignment	2.4km
Total	30.5km

Stations	
Elevated	6
Underground	1
At-grade enclosed box	1
Part at-grade /part underground	1

Operating statistics	
Operating hours	5.30am to 1.30am
Initial planned headway	three minutes
Initial (current) operation	seven-car trains
Ultimate headway	105 seconds
Ultimate operation	nine-car trains
Train capacity	335 passengers per car
Maximum train speed	130km/hour)
Average train speed	65km/hour (approx)
30.5km journey time	30 minutes (Tuen Mun to Nam Cheong)

Colin Wade is an Associate Director of Arup in Hong Kong. He led the re-engineering of Tsuen Wan West station following the value engineering exercise and was Registered Structural Engineer (RSE) for the project. He has also taken up various engineering roles on all Arup's East Rail extension projects as well as the Kowloon Southern Link feasibility study.

1. Long viaduct spans across the Kam Tin River.

The Yuen Long section: viaducts and stations

Naeem Hussain Michael Kwok

Introduction

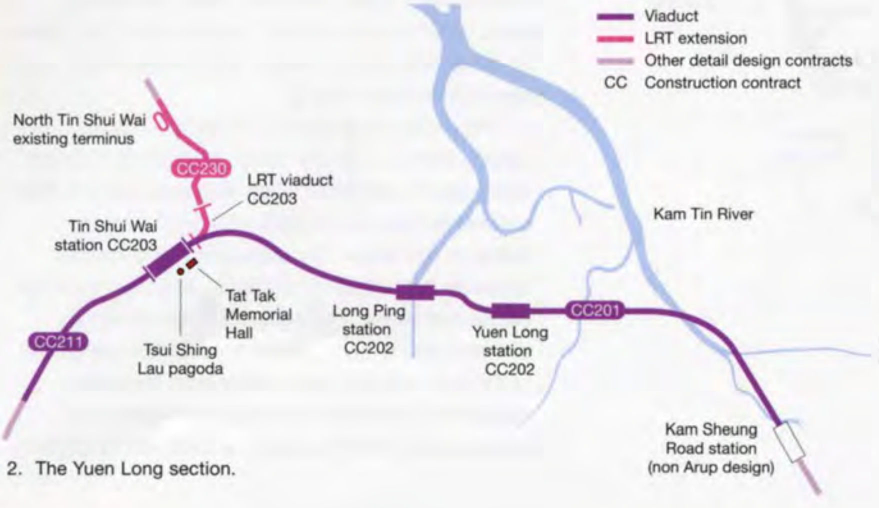
The Yuen Long section, the largest single design package on West Rail, is 8.8km long. A viaduct comprises 7.6km of this length, the remainder being the three elevated stations at Yuen Long, Long Ping, and Tin Shui Wai (Fig 2).

Arup as lead consultant was responsible for all aspects of the design, including architecture, landscaping, route civil engineering works (roads, drainage and utilities), the stations' structural, electrical and mechanical design, and the viaduct itself. The firm was also concept designer[1] for the entire 13km viaduct length, part of which was in other design packages. Typical viaduct spans are 35m, the longest, in the Kam Tin River area, being 90m (Fig 1).

The line passes through existing wetlands (marshes), built-up areas of Yuen Long and Long Ping, and future urban development close to the railway.

Yuen Long station, next to the existing Sun Yuen Long Centre, has been designed to carry six 38-storey residential developments directly above.

Tin Shui Wai and Long Ping stations are stand-alone, but have adjoining passenger transport interchanges designed for future multi-storey property development above. The routing through built-up areas required extensive diversion and construction of roads, drainage, and utilities.



2. The Yuen Long section.

Environmental considerations

These included safeguarding and enhancing the wetlands, noise attenuation, and minimizing visual impact.

The design of the stations and viaduct was most influenced by the Hong Kong Noise Control Ordinance (NCO), instituted in the early 1990s, which sets statutory noise limits on the operation of railways and other sources. At night (2300 - 0700), operational noise levels along sections of the West Rail alignment must not exceed 55dBA at the façades of noise-sensitive receivers.

To meet this limit at all properties outside the railway boundary, with the proposed peak night-time headway of four minutes, the maximum noise level must not exceed 64dBA at 25m from track centre for nine-car trains travelling at 130km/hr. With an assumed reference wayside noise level of 88dBA for an unmitigated viaduct, the law required a 24dBA noise reduction.

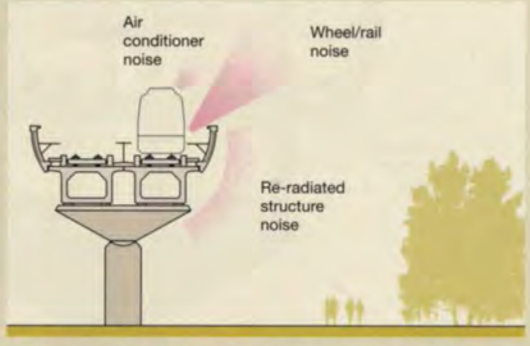
Total wayside noise from a train passing primarily comprises:

(1) direct (airborne) noise from the undercar generated by wheel/rail interaction and the propulsion system

(2) structure-radiated noise from vibration transmitted through the trackform

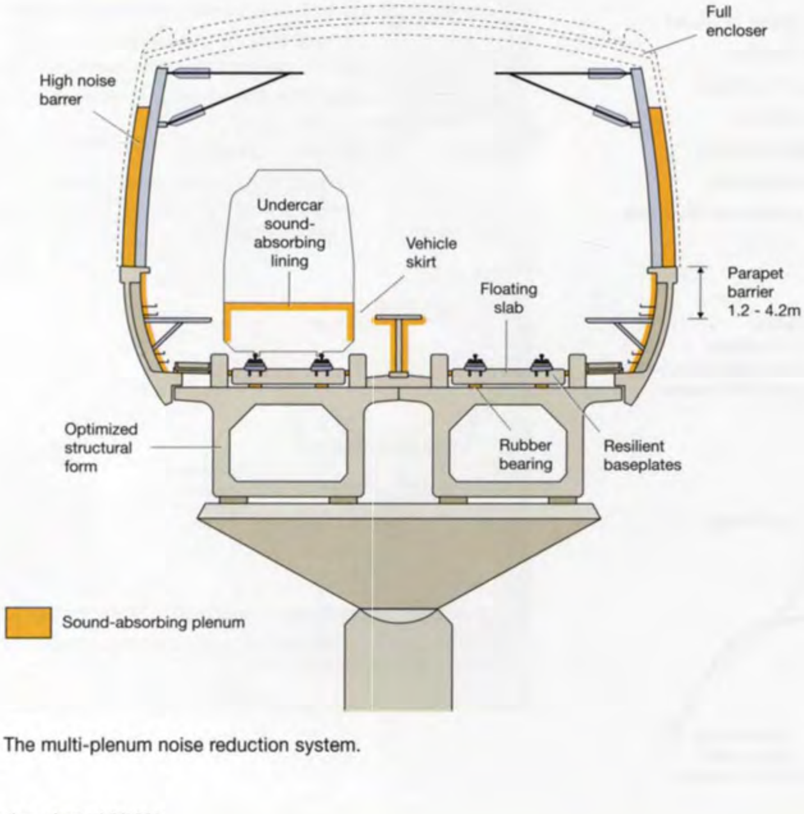
(3) air-conditioning system noise (Fig 3).

If (3) is adequately limited, achieving compliance for total wayside noise requires significant reductions in both (1) and (2) to a maximum level for each of 61dBA.



3. Constituents of the total wayside noise from a train passby on a viaduct.

4. Yuen Long viaduct from the air, approaching Tin Shui Wai on the left.



5. The multi-plenum noise reduction system.

Viaducts

Attenuation of airborne noise

A simple edge wall barrier, with or without sound absorption, could not alone reduce airborne train noise by 27dBA, so additional mitigation was needed. The adopted scheme, the multi-plenum noise reduction system, has three principal components: (1) an undercar sound-absorbing plenum; (2) "under-walkway" sound-absorbing plena on either side of the vehicle; and (3) edge walls with sound absorption (Fig 5).

The undercar plenum is created by placing vehicle skirts on the car sides, particularly over the axles, and by installing noise absorption on the floor underside near the bolsters and on the interior facing of the skirts. The plenum outlet is formed between the bottom of the skirts and the top of the derailment kerbs. The system's noise-reduction effectiveness is partly determined by the size of the outlet gap, smaller being better from the noise standpoint. Kinematic envelope and clearance requirements limit this gap to a minimum of 250mm.

The under-walkway plenum on the viaduct wayside is bounded by the parapet, the deck, the walkway, and the vehicle. Sound absorption is placed on the edge wall and the walkway underside. The plenum outlet is the gap between the walkway and the vehicle, again limited by the vehicle kinematic and curvature envelopes. For West Rail, the minimum gap size is 250mm on straight track and 350-400mm on curves. Derailment safety requires that the vehicle can move laterally by roughly 600mm during derailment, implying that the walkway must be friable and minimize impact load to prevent damage to or detachment of the concrete parapet from the deck. The under-walkway plenum at the viaduct centre is bounded by a median wall, the deck, the top plate, and the vehicle. Because of viaduct width limitations, this plenum has less volume than those under the edge walkways, and so is not as effective in attenuating noise.

A comprehensive noise model of the multi-plenum system, combining plenum and sound wall attenuation equations, was developed. Before predictions were made regarding the West Rail system, this model was validated against data taken on skirted trains, absorptive parapet walls on transit viaduct structures, and close-in sound barriers adjacent to a transit train undercar. The multi-plenum system satisfied the design maximum of 61dBA on both the wayside and trackside for parapet walls 2.9m high above the deck (Table 1).

Attenuation of structure-borne noise

Structure-radiated noise from trains (130km/hr at 25m setback) on a concrete viaduct, with stiff rail fixings and no particular attention paid to noise aspects of the viaduct section, is roughly 80dBA. A structurally-similar section in steel is about 10dBA higher. It was resolved early that the West Rail viaducts would be simply-supported structures with a concrete twin box section and the deck stitched together along the viaduct centreline. A concrete box girder is ideal for resisting torsional and overturning effects from wind loading, especially on the high-sided noise barriers. This meant a reduction of about 19dBA was required for the West Rail viaducts to comply with the NCO. Additionally, rumble noise is limited to 72dB in any low frequency 1/3 octave band.

The team developed a structure-borne noise model to predict wayside noise levels and help design development. Starting with a suitable wheel/rail roughness spectrum, vibration levels were calculated in the structure using a finite element analysis, and vibration levels were converted to noise using analytical formulae.

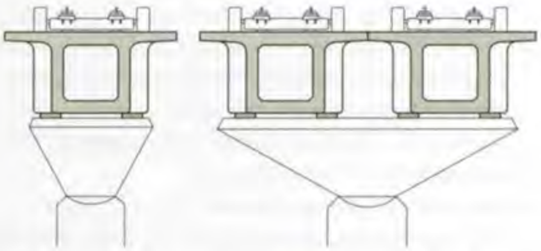
Before making predictions for West Rail, the model was validated against vibration and noise measurement data taken on the MTR Corporations's covered viaduct structure on the Tsuen Wan line between Kwai Fong and Kwai Hing stations in Hong Kong, and on the MARTA system in Atlanta. Rail vibration levels measured on the A-13 viaducts on the WMATA system in Washington and measured vibration-to-noise conversions obtained from Hong Kong's Tsing Ma suspension bridge provided other validations.

The study considered design variations in type of trackform, mass and stiffness of the section, deck thickness, distribution of mass and stiffness (ie number, size and location of fillets and webs), and noise radiating area. There were two major findings. Firstly, a floating slab trackform (FST) with soft baseplates was required, regardless of how much the viaduct cross-section was optimized with respect to noise. Secondly, the viaduct section did have to be optimized regarding noise.

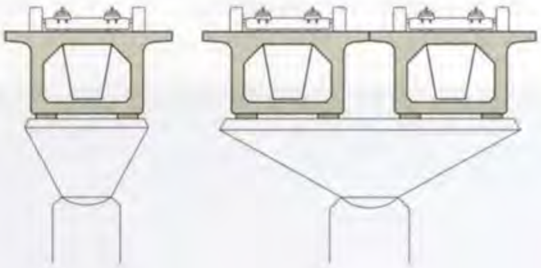
Ideally, the box girder webs should be placed directly under the FST rubber bearings to increase the mechanical impedance there and improve the trackform's vibration isolation. Doing this, however, results in narrow spacing of the webs leading to overturning instability. Analysis showed that either of the two possible solutions (Figs 6, 7) would lead to an acceptable section for noise attenuation. To reduce the extent of structure surfaces that radiate noise, the width of the top slab was kept to a minimum. This resulted in an outer slanted curved parapet that both accommodates the trackside evacuation walkway and gives the required volume for the noise plena.

Table 1. Airborne noise levels (Lmax) for edge barriers with and without the plenum system at 25m setback and level with top of rail.

Location	Mitigation	Edge barrier height	
		0.0m 1.0- dBA	2.9m - dBA -
Wayside	Parapet wall only	88	72
Wayside	Parapet wall with plena	–	56
Trackside	Parapet wall only	88	75
Trackside	Parapet wall with plena	–	61

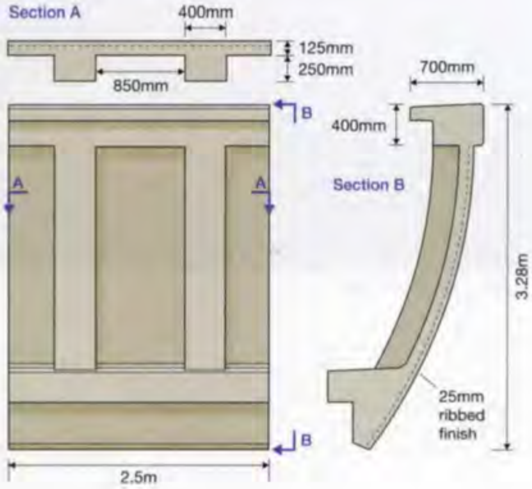


6. Narrow web spacing, with a diaphragm at the pier supports to increase spacing between bearings.



7. Wider web spacing to increase the distance between bearings, with large fillets between the deck and girder webs to decrease vibration of the deck.

8. Typical outer parapet.



In Table 2, predictions of airborne, structure-radiated and total wayside noise are given for the optimized viaduct section (wide-spaced webs plus fillets) for three different trackforms: resiliently-booted sleepers (LVT), soft resilient baseplates only, and FST with soft resilient baseplates. The structure-radiated noise from the top deck and the FST slab is included in the airborne noise, as it is attenuated by the multi-plenum system. It can be seen that only the optimized viaduct section with the FST system satisfied the noise target of 64dBA.

Superstructure aspects

To avoid vibration resonance between train, trackform and viaduct, leading to adverse ride quality, the following were specified:

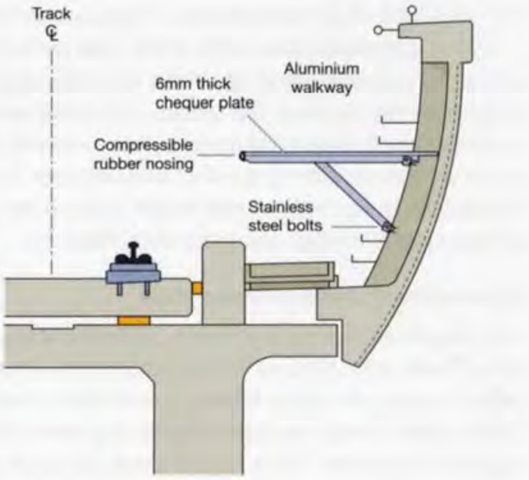
- frequency of the fundamental longitudinal flexural mode of a typical span to be in the range 2.6-5Hz (actual frequency of the deck: 3.6Hz)
- resonance frequency of the rigid viaduct in vertical motion acting against the bridge bearings atop the piers to be in the range 25-30Hz
- fundamental resonance frequencies of the rigid viaduct on the bridge bearings, the lateral and longitudinal flexural bending modes, and the torsional bending mode of a typical span sufficiently separated from the resonance frequencies of the FST (14-18Hz), the primary suspension (5-10Hz) and the secondary suspension (1-1.5Hz) of the train
- ride quality in trains on the viaducts at planned operational speeds to satisfy the four-hour reduced comfort boundary in ISO Standard *2631*[2].

These requirements, together with the necessity to cater for the overturning effects of wind on the high noise barriers, led to the choice of a concrete box girder superstructure - the section with wide web spacings, rather than that with narrow web spacing and end diaphragms.

9. The parapet in use.

Table 2. Noise levels estimated on the trackside for the optimized viaduct section.

Trackform	No noise mitigation (dBA)	Airborne noise (dBA)	Structural noise (dBA)	Total noise (dBA)
Soft baseplate	88	62	75	75
LVT	88	62	74	74
FST	88	63	58	64



10. Walkway design.

Parapets and walkways

Mass was needed to prevent noise transmission through the parapets. The minimum thickness to achieve the required specification was a 75mm thick concrete wall, which needed to continue 1.2m above the walkway level. The resultant parapet on the outer face is 3.28m high, leaning out from the superstructure box edge (Figs 8, 9). These outer parapets carry not only their own weight but also the high noise barriers and full noise enclosure, and the parapet module length was chosen as 2.5m with two stiffening ribs. In addition, the concrete stitch between the precast parapet unit and the top flange of the superstructure had to be strong enough both to carry the weight of the parapet unit, noise barriers, noise enclosures and walkway, and resist the impact load generated by the walkway in the event of train derailment.

The walkway had to have sufficient mass to meet the noise transmission specification, be light enough to reduce superimposed load, and have enough strength and stiffness to cater for crowd loading from a derailed or stalled train. Again, it needed to be friable in the event of train derailment, not causing excessive damage to a derailed train nor imposing excessive loading on the concrete parapet to cause its failure, and be durable with minimum maintenance.

These conflicting requirements led to the choice of 6mm thick aluminium plates supported on an aluminium frame (Fig 10). The horizontal load on the concrete parapet, from in-plane buckling of the aluminium plate caused by a derailing train, had to be minimized, and realtime dynamic analysis on the Arup program *DYNA3* showed that three overlapping plates, rather than a single one, were required to reduce the generated force so that it did not cause a catastrophic failure of the concrete stitch connecting the outer parapet to the superstructure.

Noise barriers and full noise enclosure

Where the viaduct runs close to existing buildings, additional high noise barriers above the concrete parapets were installed, and full noise enclosures were needed at points and crossings as these generate an extra 10dB. These barriers and enclosures comprise acoustic panels on steel frames, with an exterior cover in profiled aluminium sheeting (Figs 11, 12). All twin-track viaducts can support full noise enclosures for noise attenuation near future development.

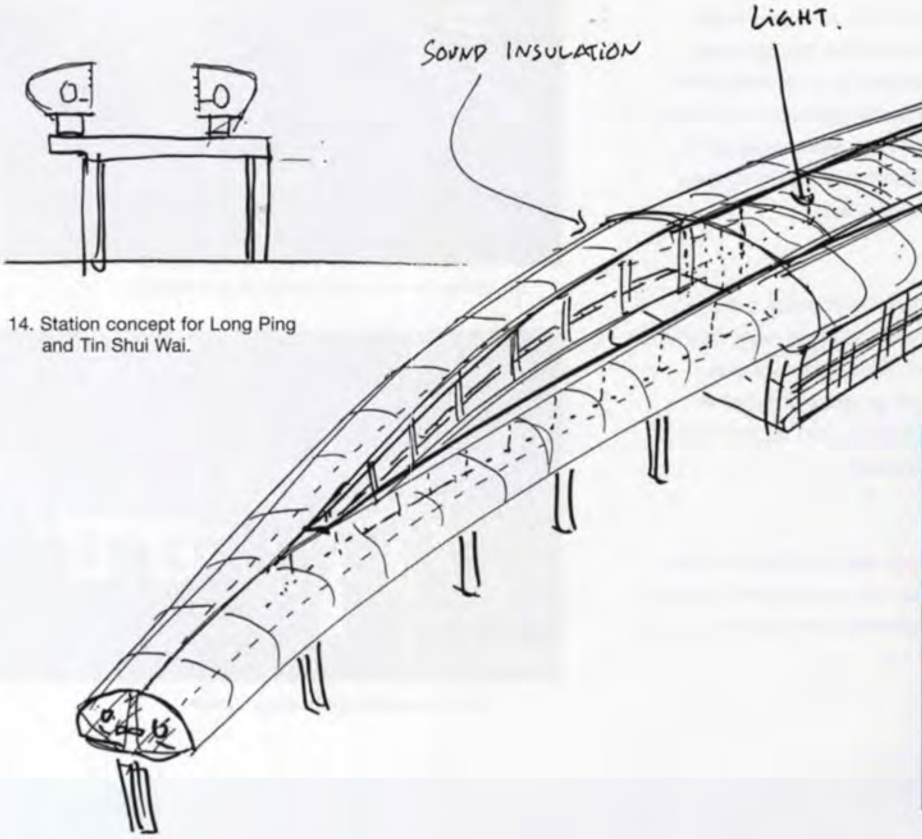
Design progress at construction stage

During construction, the box girder with wide web spacings was replaced by one with narrow web spacings and a monolithic connection to the slender pier columns, which avoided the overturning problem associated with bearings and led to a more visually pleasing and maintenance-friendly structure (Fig 13).

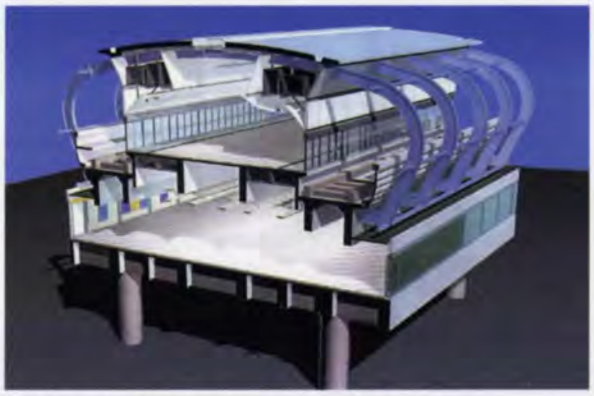
12. Design for full noise enclosure at crossings.

13. Final as-constructed viaduct design.

11. The full noise enclosure in use, adjacent to Pok Oi Hospital at Yuen Long.



14. Station concept for Long Ping and Tin Shui Wai.



15. Typical section through structure for Long Ping and Tin Shui Wai stations.

16. Computer visualization: Long Ping and Tin Shui Wai stations.

Stations

Concept

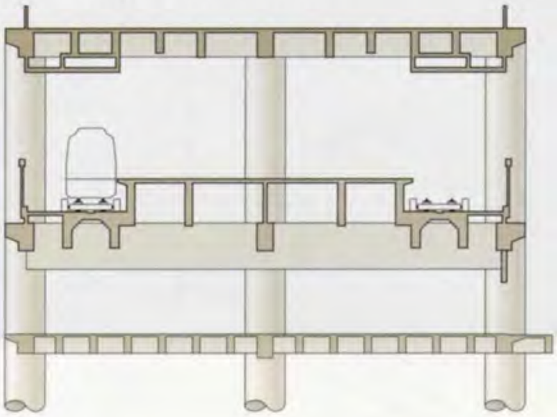
There was a strong desire for structural and visual harmony between the viaducts and the stations, particularly at Long Ping and Tin Shui Wai as there was to be no development above them, and ground level constraints naturally favoured similar long-span structures for the stations. The twin box viaduct structures could be split to run through each station on either side of the island-type platform, and the curve of the full noise enclosures originally envisaged on the viaduct could naturally lead into a curved roof on the stations, providing visual harmony (Fig 14).

The typical station layout therefore has two levels. The lower accommodates paid and unpaid concourse, railway operating services facilities, ticketing kiosks, station trading, back-of-house facilities, and plantrooms. The upper comprises an island platform track carrying structure, additional railway operating service facilities, and plantrooms. At Long Ping and Tin Shui Wai this allowed the platforms to be column-free, but this was not possible at Yuen Long due to the requirement for property development directly above.

Design development

At detailed design stage, the prestressed concrete box viaduct structure was replaced with twin beams (as near as possible beneath the rails). These support the track slab, and span between main crossbeams in turn supported by columns (Fig 15). The roofs of Tin Shui Wai and Long Ping stations are exposed curved steel frames that carry the central glazing and building services (Fig 16) but at Yuen Long these are replaced by a reinforced concrete deck for the future development. Three rows of columns through the station will support future transfer structures to carry the residential towers (Fig 17).

17. Yuen Long station: cross-section.



18. Central rooflight at Tin Shui Wai station.

19. Full-height "slit" windows at Tin Shui Wai station.

Architectural considerations

Tin Shui Wai and Long Ping

The steel roof is the most prominent feature, and was profiled to suit the structural performance as well as to support elements such as platform screen doors, air-conditioning system, lighting, etc.

A central linear roof light brings natural light to the platform and ultimately down to the concourse through the stair and escalator voids (Fig 18).

The off-white aluminum platform ceiling soffit is shaped to suit the air-conditioning system and artificial lighting pattern, and is also perforated to meet the acoustic performance requirements. The "unpaid concourses" are the busiest parts of the stations, functioning as their main entrance areas and demarcated by full-height windows that provide a high degree of natural lighting, enhance the dynamic nature of the space, and create a rhythm along the external façade (Fig 19).

The windows visually link the interiors and exterior and enable passengers to orientate themselves. The circulation elements along the central axes of the stations are lit directly and indirectly, with grey resin-based terrazzo flooring to complement the off-white wall panels. The overall atmosphere is calm and soft to counteract the dynamic nature of the stations. Footbridges connect them with street level and some adjoining buildings.

The roofs are covered by non-reflective aluminum to avoid glare to the surrounding buildings in these congested neighbourhoods. The essence of the design is simple and sophisticated to reflect the functional nature of the station architecture and create a distinct image for the Yuen Long district (Fig 20).

Yuen Long

The concept here maintains the two-level concourse/platform arrangement with neighbourhood access by footbridges and staircases. However, the rectilinear box-like structure under the substantial concrete deck necessitated by the scale of the planned development above gives less opportunity for natural light into the concourse and platform. Internal circulation elements remain on the central axis as for the other two stations but a central row of columns has been introduced to carry the roof deck and future loads.

20. Tin Shui Wai station.

21. Roof cladding at Tin Shui Wai station.

Constraints

Co-ordination with numerous authorities and utility providers was vital during design and throughout construction in these highly congested urban areas (Figs 21, 23, and 24). At Yuen Long, the station is integrated with the existing Light Rail Transit (LRT) terminus beneath the adjacent Sun Yuen Long Centre and is overlooked by the residential blocks above this development. Environmental noise issues were constraints throughout construction. Long Ping station was built in a congested network of busy roads and above two nullahs (large open-top man-made stormwater water run-off collection channels: Fig 25).

Tin Shui Wai at some 480m long is the largest West Rail station. It is sited next to Tin Fuk Road and spans the busy junction of this road with Tin Yiu Road and Ping Ha Road, all of which accommodate the LRT (Fig 26). A new LRT stop has been provided at ground level beneath the station with its platforms linked to the West Rail platforms via lift, stairs and escalators (see also pp18-19).

Geotechnics and foundations

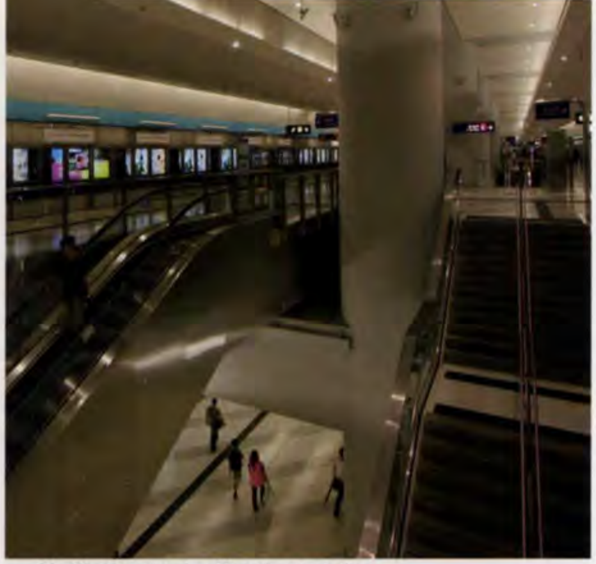
The Yuen Long section crosses a marble (karst) area with extensive large caverns, and so the viaducts and stations have to be carried on piles with founding levels having at least 20m of proven rock below them. At Yuen Long station, with future 38-storey towers above it, an extensive site investigation was undertaken with boreholes based on a 3m grid (see pp20-22).

Structures

Tin Shui Wai and Long Ping stations

Structurally, these are identical, the differences being their lengths and substructure arrangements. The structure comprises a series of two-storey reinforced concrete portal frames at 24m spacing along the trackway carrying the concourse zone at first floor level and the platform and trackways at second floor (Fig 15). Longitudinal stability is provided by frame action between the portals and deep longitudinal reinforced concrete beams that support the trackways and concourse levels. Spanning clear over the platform and trackways is the roof of arched steel portal frames, at 6m spacing and unclad over the trackways.

The portals are I-beams fabricated from welded plates, fixed to the perimeter trackway edge beams, and stabilized longitudinally by a combination of cross-bracing at roof level and circular hollow sections along the trackway zones.



22. Platform level at Yuen Long station.

The platform is separated from the trackways by platform screen doors (Fig 27), hung from the portal frames via secondary steel frames as are the electrical and mechanical services, air-conditioning ductwork, lighting, and suspended ceiling units.

Yuen Long station

Unlike the other two, this structure comprises a series of three-storey two-bay reinforced concrete portal frames, generally at 12m spacing along the station, which form the base structure to carry all lateral and vertical loads from the future towers above the station. To design the station structure and foundations, the towers were scheme designed to arrive at all load combinations, and the scheme design will form part of the control brief for future development. The reinforced concrete roof above the trackway and platform forms the required four-hour fire separation between the future development and the railway. The deck also forms the future development contractor's base and has been designed for superimposed construction loads that will also be set out in the control brief. All columns are built with projecting stubs above roof deck level with embedded couplers to allow future extensions (Fig 23).

Whilst numerous underground stations in Hong Kong have been designed for air rights developments either above or alongside, it is relatively unusual for an elevated station to have tall towers directly over the platform and trackway zones.

Construction

Construction contracts were awarded in July 1999 for CC203 (Yuen Long and Long Ping) and September 1999 for CC202 (Tin Shui Wai). Piling works were a priority at all three, to enable superstructure works to proceed and allow connection with the adjoining viaducts.

A great deal of ground level works were needed to divert and upgrade major utilities and services, move roads both temporarily and permanently, reinstate public facilities, and maintain public rights of way. Numerous temporary traffic management (TTM) measures were put into place throughout the works. These were planned at design stage and included in tender documents in schematic form. TTMs needed approval by the site liaison group (SLG), a formal committee required for railway and public infrastructure projects to vet and approve temporary traffic arrangements. For railway infrastructure work the SLG is chaired by the Government's Railway Development Office and, depending where the project is, can include a significant number of government agency representatives ranging from the police, fire services, transport department, and drainage services through to the departments responsible for leisure, culture, tourism and the postal services. SLGs are attended by the contractor, resident site staff, and design office representatives – a formidable meeting in most instances! For Tin Shui Wai station over 100 separate TTMs were submitted and endorsed by the SLG.

23. Yuen Long station in context.

For any works near the existing LRT, a permit to work had to be issued by the KCRC's LRT Department, each one taking roughly two weeks to process. As for all West Rail work, the station civil contractors were required to interface with railway operating system (ROS) contractors as well as other adjoining civil contracts. Numerous co-ordination meetings were held to incorporate ROS requirements and arrive at a co-ordinated installation programme, the many ROS contractors requiring the co-ordination and resolution of issues such as access for labour and materials, storage, safety, security, fire hazard, debris disposal and sanitation.

Construction supervision

A large number of resident site staff were deployed for the Yuen Long section under the leadership of Arup to cover all disciplines including architecture, landscape works, and claims/cost control. The resident site staff comprised a chief resident engineer with three senior resident engineers to oversee the two station contracts CC202/203 and the two viaduct contracts CC201/211. Discipline heads made regular reports, with regular and ad hoc meetings between senior resident engineers and contractors' staff to resolve problems. All temporary works had to be certified by an independent checking engineer employed by the contractors. In addition, all major sub-contractors were approved by the KCRC, which made safety a top priority from the commencement of the West Rail project.

The resident site staff were authorized to issue safety and corrective action requests for any deficiencies that could have led to unsafe situations, and also had the authority to issue suspension of works notices. External and internal safety audits were conducted twice yearly throughout construction. Internal audits were conducted by KCRC whilst external were performed by Det Norske Veritas, the Oslo-based risk management consultancy.

25. Long Ping station is constructed over stormwater collection channels (nullahs).

26. Tin Shui Wai station links to the existing LRT system.

24. Long Ping station in context.

27. Train at rest in Tin Shui Wai station, with platform screen doors open.

Construction progress

Due to the location of the stations in the cavernous marble areas of Yuen Long, piling works faced numerous difficulties and initially maintained only a slow rate of production. Some bored piles exceeded 100m in depth due to the strata encountered, one at Long Ping station going down 129m: this is believed to be the longest bored pile so far constructed for a Hong Kong railway project.

Piling was finally completed at Yuen Long station in November 2001; superstructure followed rapidly, and was completed in March 2002. Substantial completion of all other civil works for the entire Yuen Long section was completed the same month, in line with the KCRC's target completion date. Follow-on works proceeded rapidly during the remainder of 2002 with trackwork completed by August. June 2003 saw all stations complete with trial revenue operations commencing the same month.

Conclusion

These very large station structures will serve their busy local communities for many years to come. With the location as a first constraint plus the additional issues of the existing urban civil infrastructure and the extremely difficult geotechnical problems, all concerned made a significant achievement in this complex multidisciplinary project. Including as it did a wholesale line-wide value engineering exercise, it is remarkable that only 5.5 years saw the full detailed design, tender documentation, procurement and construction, up to trial running, of Hong Kong's first totally new urban railway.

References

(1) HUSSAIN, N *and* CROCKETT, A. KCRC West Rail viaducts: design development: in "Current and future trends in bridge design, construction and maintenance", Thomas Telford Publishing, 2001. (Paper presented at the Institution of Civil Engineers international conference on bridge engineering, Hong Kong, 25-26 April 2001).

(2) INTERNATIONAL ORGANIZATION FOR STANDARDIZATION. *ISO 2631*. Evaluation of human exposure to whole-body vibration. ISO, 1985.

Historical companions

Apart from high rise estates, three schools, and nearby villages, Tin Shui Wai station is also near two historical structures. The closer is Tsui Shing Lau (Fig 28), Hong Kong's only authentic ancient pagoda dating from the 14th century, early in the Ming dynasty (1368-1644). It is small and modest by mainland standards but has a special and honoured place in the local tradition of the district of Ping Shan which adjoins the station.

The pagoda is a six-sided structure about 13m high, built of Chinese grey bricks, and intricately arranged brick corbels delineate its three storeys. It is said to have been originally built as a seven-storey structure but the four upper storeys were lost, most likely due to typhoons. Inside is an altar with wooden deities but the building is neither a temple nor a Buddhist shrine, but principally a fung shui (good fortune) structure. Local people relate that it was built as a protection against "unfavourable influences from the North" – possibly evil spirits.

A little further from the railway alignment is the Tat Tak Memorial Hall, an ancient building, probably owned by the whole village as a communal venue for ceremonies to worship their ancestors. It is very dilapidated but being of historical value was required, along with the pagoda, to be preserved by the Government Antiquities & Monuments Office, which required movement monitoring to be undertaken throughout construction.

28. Tsui Shing Lau pagoda, showing ornamental brick corbelling.

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Michael Kwok is a Director of Arup in Hong Kong and mainland China, and general manager and leader of Arup's Beijing office. He was structural team leader for the Yuen Long section stations.

1. Viaduct across Tin Fuk road carrying light rail in and out of the at-grade platforms under Tin Shui Wai station.

2. Typical light rail stops match those on the existing system - also designed by Arup, in the mid-1980s. This stop is at Tin Wu.

3. Modifications to Tin Wing terminus in North Tin Shui Wai.

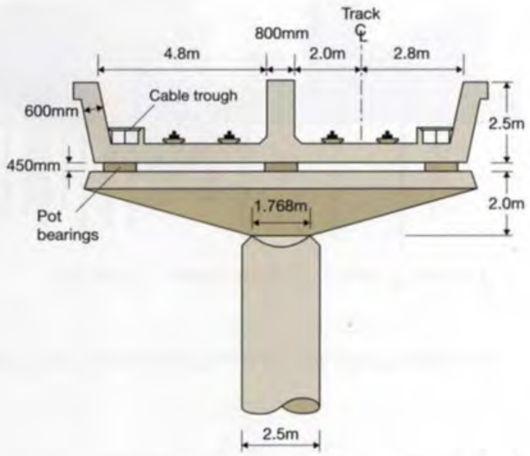
Light rail transit: Tin Shui Wai extension

Fergal Whyte

Arup's original involvement in the light rail network stemmed from being the contractor's designer on the original LRT system between Tuen Mun and Yuen Long in the mid-1980s. After this first phase came extensions within these new towns and the newer town of Tin Shui Wai as these areas were developed. The implementation of West Rail, also linking Tuen Mun, Tin Shui Wai and Yuen Long, was an ideal opportunity to transform the LRT into a feeder for the West Rail service, and so interchanges at Tin Shui Wai and Yuen Long were provided, with extensions of the existing network into newly populated areas to provide better access to West Rail.

Arup's appointment on the West Rail DD200 design consultancy included a 3km LRT spur line into Tin Shui Wai, involving a 150m long viaduct (Fig 1), three new LRT stations (Fig 2), an interchange station with the Tin Shui Wai West Rail station, the modification of existing termini at North Tin Shui Wai (Fig 3) and Yuen Long, and associated rectifier substations to provide power to the new LRT line. The LRT station at the Tin Shui Wai Interchange comprises three 90m long at-grade platforms directly beneath Tin Shui Wai West Rail station (Fig 4).

4. New LRT platforms beneath Tin Shui Wai station.



6. Typical section through LRT viaduct.

The viaduct design was constrained by the very tight headroom directly above the existing Tin Fuk road, which resulted in a U-form in situ prestressed concrete structure with a very thin base slab (Fig 6). The main structural members are in fact the parapets either side of the trackwork, as there is only room for a 450mm deep structure due to the lack of available headroom above the road. This was despite needing to go to the maximum gradient, 6.246%, used elsewhere on the LRT.

The design of the three intermediate stations followed that of those already on the network. One critical safety issue was the design of the at-grade junctions with a traffic/LRT interface. Detailed simulations, and extensive discussions with LRT operational staff and local government representatives, ensured this was dealt with to the satisfaction of all parties.

The trackwork is formed on ballast and sleepers for most of its length (Fig 5), except on the viaduct, where the rails are fixed directly on a concrete plinth cast into the viaduct base slab, and at road crossings, where it is boxed-out within the concrete road slab (Fig 7). Subsoil drainage is provided for the trackbed, and power supplied via overhead lines with mast supports between the tracks.

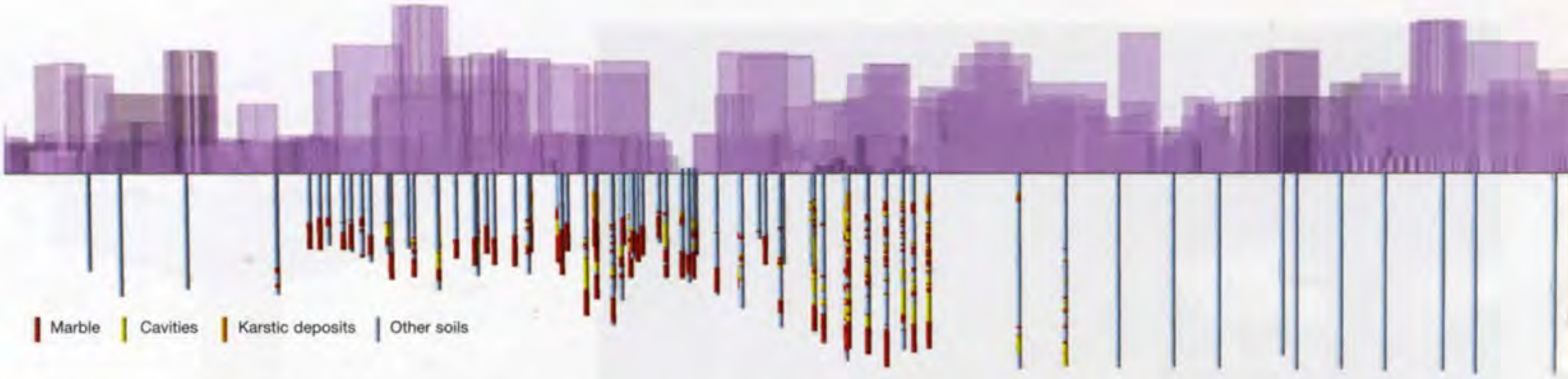
Construction of the LRT work had little impact on local residents. The extension had been included from the very early stages of planning Tin Shui Wai, and so an 8m wide reserve was available. This was devoid of any services, allowing construction of the permanent works to commence almost immediately upon award of the contract.

With the opening of the new Tin Shui Wai extensions on 7 December 2003, the LRT network was extended to a route length of 36.15km with 68 stops.

7. Typical road crossing where the trackwork is boxed out within new road slab

5. This view between the stops at Tin Wu and Ginza shows the 8m wide reserve in which the LRT extension was built.

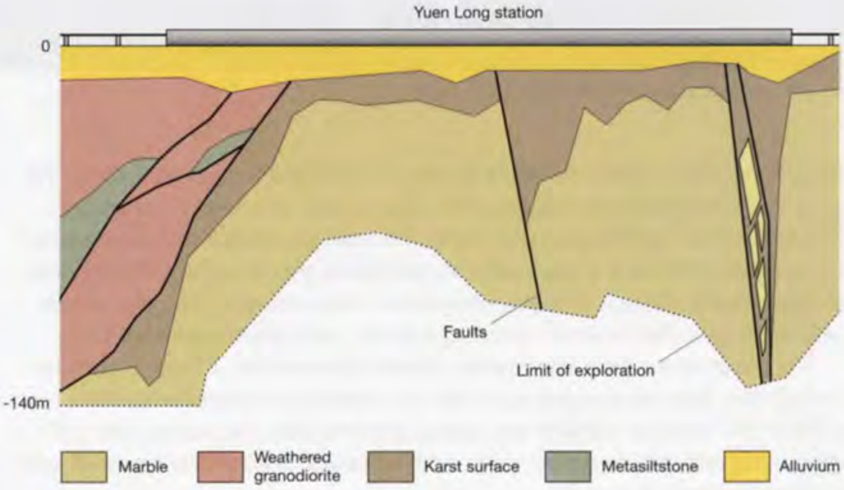
Fergal Whyte is a Director of Arup in Hong Kong. He was responsible for the design and co-ordination of the light rail transit extension for KCRC at Tin Shui Wai, and of the ground level works associated with the Tin Shui Wai West Rail station and the adjacent public transport interchange.



1. Geological section from Long Ping (left) to Yuen Long (right).

Piling in Yuen Long: a unique experience

Daman Lee Jeffrey Lo



2. Simplified geological model at Yuen Long station.

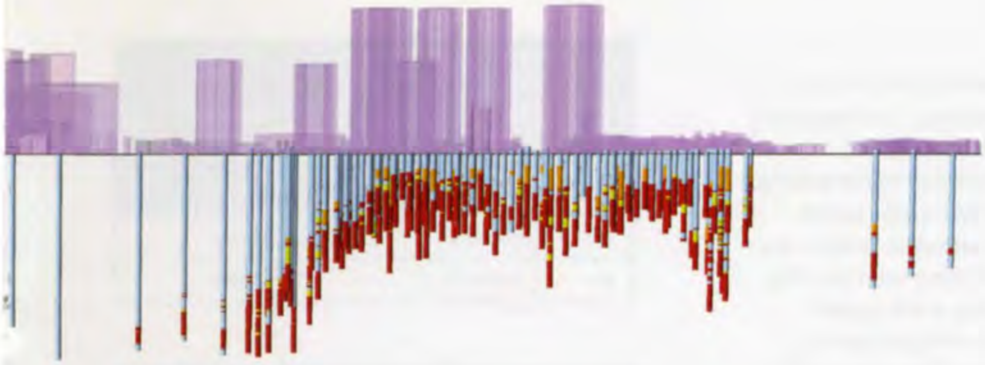
One of the greatest challenges in Hong Kong foundation engineering is how to transfer heavy column loads within cavernous marble bedrock. Though such adverse geology is found only in three small areas in the New Territories - Yuen Long to Tin Shui Wai, Ma On Shan, and to a lesser extent along the north hinterland of Lantau Island - along the 8km Yuen Long section of West Rail there are three distinct locations with abundant marble bedrock. All were selected for siting a station! In the early study stages of West Rail, geological considerations unfortunately had much lower priority than factors like patronage, land premium, connection with existing transportation systems, town planning, future developments, etc.

A geological section between the stations at Yuen Long and Long Ping clearly shows the adverse ground conditions at the station sites and their absence in the viaduct section between (Fig 1). The foundations at all three stations and some viaduct sections immediately adjoining them were major challenges to the design team.

The marble rocks at the three stations have very contrasting forms. At Yuen Long they are relatively pure. Near rockhead, which varies from 25m to over 105m below ground within the length of the station, serious *karst* features exist in a way that is extremely aberrant (Fig 2). Two boreholes at the same location frequently resulted in a difference in rockhead by tens of metres simply because of deviation from the drilling process! Faulting and fracturing also created serious cavitations in the rock mass. Drill strings used to form boreholes were observed to drop metres without ample warning.

The situation is quite different at Long Ping, just 1km away. The rock here is marble interbedded meta*siltstone*, forming a transitional zone between the underlying Yuen Long formation and the Lok Ma Chau formation above. Any cavitations were found to have been infilled with *metasediment* and this interbedding sometimes continued to depths beyond 100m, giving rise to a different problem that could not be solved in the same way as those at Yuen Long. The presence of marble at Tin Shui Wai was trivial compared with the other two stations. Here, it appears as small clasts within the *tuff/pyroclastic rock mass*.

At the time of the design, there was still relatively little experience in Hong Kong in dealing with such variable and extreme ground conditions. Fortunately, the same design team was in place throughout, from planning the original ground investigation until completion of foundation construction. This was invaluable, as design checks and adjustments were continuously needed as more ground information was revealed by the piling. Throughout the project, innovative approaches were needed to achieve cost effectiveness and the tight programme. The following are a few highlights.

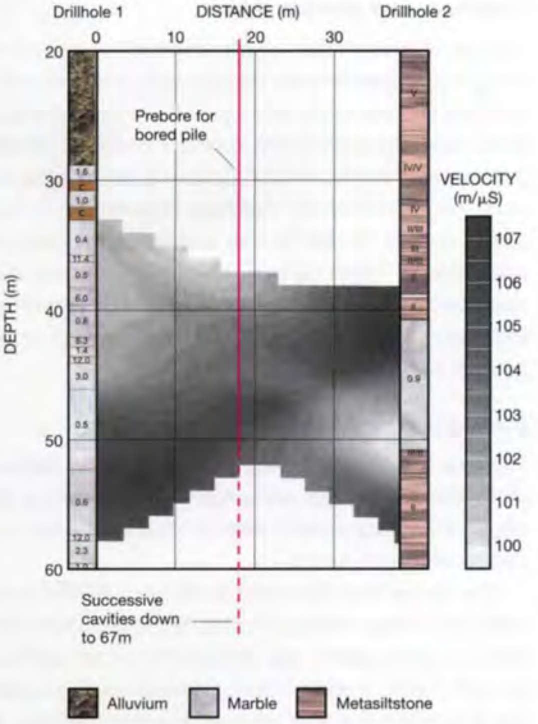


Ground investigation

A natural gamma ray sensor and an induction probe were combined into one *sonde* and used in boreholes to obtain information on the nature of the *karst* features and the soil and rock *lithology*. The gamma investigation technique utilizes the fact that carbonate rocks emit low natural gamma rays, unlike the much higher gamma counts from the radioactive components of materials like clay that are prevalent within the *karst* surface. The gamma count is also high in *mudstone* strata, less in *siltstone*, and lower still in *sandstone* and *quartzite* rocks. In a typical borehole, the gamma radiation picked up by the instrument is mostly from a zone within 300mm of the drillhole wall, but with the emissions from the marble being low, there is a chance of detecting bodies of clay at slightly greater distances.

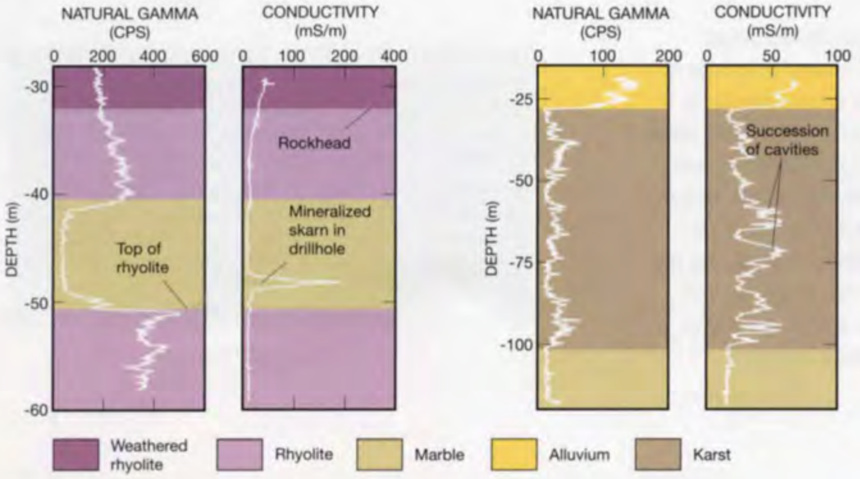
The induction tool comprises a transmitter and receiver coil set 500mm apart. The induction probe determines the presence of high conductivity material within 1.5m of the hole. On average, low porosity unweathered marble has low conductivity. The induction probe models the *karst* zone accurately, and in several instances, demonstrated a thickness of *karst* zone that was different from that predicted from the drillhole log alone (Fig 3). In some locations, this tool effectively functions as a 3m diameter ground investigation borehole instead of the usual 100mm, as far as probing for cavities is concerned.

The use of cross-hole radar was also attempted between preselected pairs of boreholes. Here, the radar velocity is a function of the relative dielectric *permittivity*, and this mainly depends on the water content of the material in between. Pure *limestone* has a high radar velocity of 100-110m/μs, and has a *permittivity* of 7.4 to 9. By conducting trials, the degree of cavitations between the pairs of boreholes could be revealed qualitatively, giving more focused areas for further probing using closely-spaced boreholes (Fig 4).



4. Cross-hole radar tomograph.

3. Gamma/induction log.



5. Large capacity rotator was used for pile casing installation and the subsequent casing extraction during concreting.

Enhanced rock bearing stress

The use of presumptive values for design of end-bearing piles is still the norm in Hong Kong, despite such values being inherently very conservative. The West Rail advance pile test study (see pp40-41) describes the series of full-scale loading tests, including some in the Yuen Long area, in an attempt to adopt higher bearing stresses on the marble rock. Following acceptance of these test results by the Hong Kong Government Buildings Department, a maximum allowable stress in the marble rock of 11.25MPa was adopted in the design of Yuen Long and Long Ping (see Table 1). These full-scale trials and subsequent monitoring of the loaded structures provided the backbone data to allow the adoption of higher bearing stresses in the HK Government's recent revision of the piling guidance document (GEO Publication 1/2006).

Shaft-grouting in marble

The rock beneath Long Ping and the adjoining viaduct is marble interbedded with *metasiltstone*. The first encounter of marble rock is fairly consistent at around a depth of 25m but cavities exist in close succession and consistently down to depths of around 100m.

Due to the very tight programme and site constraints from the existing nullah, traffic, and major utilities all close to the proposed foundations, each column of the station support portal was designed to be carried by a single large-diameter bored pile with loads of up to 28MN. Existing practice would have necessitated the piles being founded at a level relatively free from cavities, ie up to 2.5m in diameter and down to around 100m below ground level. During installation, the excavation would have to be carried out through interbedding of rock and cavity-infilled layers. A permanent steel liner would then be placed through the section with cavities prior to concreting, to ensure a high quality pile shaft was achieved. The construction was therefore complicated and difficult, requiring several weeks (if not months) to complete each pile.

This method was adopted by the station contractor, but the adjoining viaduct contractor chose an alternative approach for piers 418-19. With programme considerations, the extreme construction difficulties and hence risks, the contractor's alternative proposal exploited his particular expertise of constructing shaft-grouted piles, which had never been attempted in Hong Kong in such ground conditions. Stability of the bore shaft supported by bentonite, and uncontrolled grout loss, were key concerns. Following extensive discussion and agreement of method statements, a staged approach of carrying out pregrouting prior to the pile excavation and subsequent post-grouting via *tubes-à-manchette* within the pile shaft was adopted. The method was tested using a full-scale trial pile to provide confidence in the adopted design parameters to the client and Government authorities (see Table 2).

"Enhanced stress"

The foundation design for Yuen Long and Long Ping, and some viaduct piers nearby, was rather more than a matter of completing designs, issuing drawings for construction, and making periodic site visits to check progress with supervising staff. Indeed, the most challenging aspect was during construction. The team came to appreciate that no ground investigation could be conducted economically and practically to ascertain the founding of these piles, as with those on granite or tuff bedrock. Apart from the design of *enhanced stress* developed for founding the piles, as discussed earlier, great stress was also put on the design team during the entire construction period. Each problem encountered, when new data came in from the continuous piling process, was unique and had to be solved quickly to avoid any significant delays. The *enhanced stress* was tested to a new limit, both for the founding rocks and the design team.

Table 1. Comparison of conventional presumptive bearing stress and enhanced values.

Rock category	Buildings Department permissible bearing stress	Design allowable bearing stress for Yuen Long and Long Ping stations
1(a)	7500kPa	11 250kPa
1(b)	5000kPa	7500kPa

Table 2. Comparison of the original and alternative designs

Pier	Original design (m)		Alternative design (m)	
	Pile diameter	Pile length	Pile diameter	Pile length
U418	2.5	45.3	2.5	30.8
D418	2.5	61.0	2.5	32.7
U419	2.0	100.6	2.5	31.7
D419	2.0	124.3	2.5	43.8

Glossary

Clasts: fragments of older rock within geological layers

Karst: geological features shaped by water action

Metasediment: sedimentary rock that has been subjected to metamorphism

Metasiltstone: siltstone that has been weakly metamorphosed

Mudstone: very fine-grained brittle sedimentary rock

Permittivity: ratio of electric displacement to the intensity of the electric field that is producing it

Pyroclastic: containing materials ejected explosively from a volcanic vent

Quartzite: sedimentary rock composed largely or entirely of quartz

Sandstone: sedimentary rock comprising sand grains plus other binding material, eg clay

Siltstone: sedimentary rock with finer grains than sandstone

Sonde: probe containing recording devices

Tuff: rock composed of volcanic fragments and dust.

Daman Lee is a Director of Arup in Hong Kong and leader of the Geotechnical group in Hong Kong. He was geotechnical discipline leader for the detailed design of the Yuen Long section of West Rail.

Jeffrey Lo is a geotechnical engineer in Arup's Hong Kong office. He has been involved in the geotechnical design of several projects for KCRC, including the Lok Ma Chau Spur Line to be featured in the future *Arup Journal* devoted to Arup's East Rail extension projects.

Tai Lam tunnel

Glen Plumbridge

Tai Lam tunnel is the largest ever built for transportation in Hong Kong, with a total length of 5.5km and maximum width of 20m. It passes beneath the hilly terrain of Tai Lam Country Park, linking the urban section of West Rail in Kowloon and Tsuen Wan with the rural section in the fast-growing Yuen Long and Tuen Mun new towns, where it emerges at its north portal on the hillside at the southern slope of Kam Tin Valley.

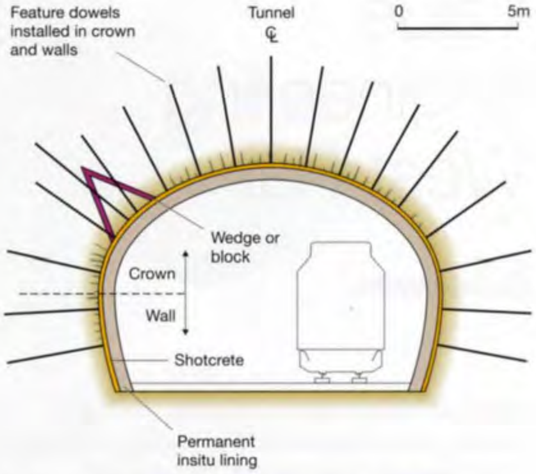
The single bore tunnel was excavated by the traditional drill-and-blast method, the two tracks being separated by a dividing wall with cross-passages at regular 60m intervals. This enables a transverse evacuation fire strategy, with passengers moving from one tunnel to the other in case of an emergency.

Nishimatsu Dragages JV was awarded the project in September 1998 under the design-build form of contract, and employed Arup as design checker for all the contractor's civil, structural, tunnelling, geotechnical, architectural, mechanical and electrical design, including - as well as the tunnel itself - two large ventilation buildings, one at each portal.

Not only did this involve detailed checking of the final designs, but also active participation in scheme development with the contractor and his designer, during which time Arup was able to add value to the project by assisting with ideas and solutions to key issues. In particular, the firm advised on the complex underpinning design for the elevated Tsuen Wan road at the south portal, where the alignment passes beneath a network of elevated, ramped, and at-grade roads at a very busy interchange. This required new foundations and a large transfer beam to be built, onto which the load was transferred from the old foundations.

As a direct appointment by the design-build contractor, this checking role enabled Arup to enjoy multidisciplinary participation with key construction personnel. As part of the checking procedure, alternatives could be reviewed and, where necessary, introduced to offer more cost-effective or faster methods (as with the underpinning of the elevated Tsuen Wan road) to help maintain KCRC's tight programme.

1. The Tai Lam tunnel north portal.



2. Cross-section through Tai Lam tunnel, showing temporary support.

3. Chai Wan Kok Ventilation Building at south end of tunnel.

Glen Plumbridge is an Associate Director with Arup in Hong Kong and was Arup's project manager for its work on the Tai Lam and Kwai Tsing tunnels (p35) and for the advance pile test study (pp40-41).

Value engineering West Rail

Colin Wade

West Rail was conceived and carried through to technical study stage as a 12-car system – identical to the operating East Rail line. This required platform lengths of some 290m and overall station lengths varying between 400m and (for Tin Shui Wai) 540m. Elevated stations generally were shorter than those underground as they did not require large plantroom spaces for tunnel ventilation.

All detailed design consultancies commenced in March 1998 based on the 12-car arrangement, and all teams provided KCRC with specified deliverables through that year. In autumn 1998, however, KCRC as part of its review procedure questioned the basic premise of why West Rail should replicate East Rail's 12-car system where stations are largely at-grade and open-sided whereas West Rail's were to be enclosed and fully air-conditioned. This question spurred KCRC to hold value engineering exercises for all parts of the project with the aim of reducing costs and, if possible, enhancing the programme.

All consultant teams undertook a series of intensive value engineering workshops in late 1998 with KCRC's project management teams to study all facets – in particular station sizing. After KCRC's own in-house deliberations, it was decided to adopt a nine-car system. This reduced platform lengths by some 72m and thus the volumes of spaces to be conditioned. To maintain the same carrying capacity the signalling system was improved, and headways reduced initially from 120 seconds to 90 seconds.

Reducing station lengths, however, increases adjoining viaducts or tunnels (albeit these are less costly to construct than stations) and so did not entirely fulfil KCRC's large cost-saving agenda. As a consequence, numerous items were revisited, studied for potential savings, and recosted. As an example, for Tsuen Wan West station a total of 68 items were brainstormed for initial evaluation by all team members. This was post-rationalized to 42 items, and ranged from overall reassessments of basement excavation methods, anti-flotation systems, column shapes, and floor structure systems through to reducing screed thicknesses, moving E&M plant above ground, reducing E&M service voids, lowering concourse ceiling height, and reducing escalator design criteria. All were evaluated for cost, programme, quality, risk and, where appropriate, aesthetics.

Many were found not to offer significant advantages over and above the design as it already stood by the value engineering study stage, but some improvements were made to the station generally, resulting in reduced length, width, and depth below ground. These were incorporated into the subsequent redesign which then proceeded rapidly to tender documentation stage. Similarly, the elevated stations on the Yuen Long section were shortened and re-engineered to yield savings.

The value engineering exercise was an interesting and worthwhile undertaking for all teams involved – co-operation and empathy between KCRC's project management teams and all consultants was of paramount importance and at the end of the exercise provided a significant benefit for the project.

Together with competitive tender prices and other beneficial factors, including lower land resumption costs, the nine-car system cost estimate for the entire project was revised downwards from the original HK$64bn to HK$46.4bn.

1. New rolling stock on the main line near Pat Heung Maintenance Centre.

1. South-west elevation of Tsuen Wan West station from the air.

Tsuen Wan West station: design and construction

WH Au Martin Mok
Richard Scott
Colin Wade KK Yin

Introduction

Tsuen Wan West station stands beside the Rambler Channel on the western edge of one of Hong Kong's first new towns (Fig 1). Arup's involvement dates back to KCRC's technical studies for the West Rail line in 1995, when this station was included in Technical Study TS300: Central Section, covering the section from Mei Foo station to the north portal of the Tai Lam Country Park tunnel (see map, p6).

After the studies, the West Rail project was divided into detailed design packages, of which DD300 comprised the station plus short lengths of cut-and-cover approach tunnels at either end of the station box linking with the adjoining design-build tunnels (DB320 and DB350). Other civil works included reclamation needed for the railway and some public facility reprovisioning works.

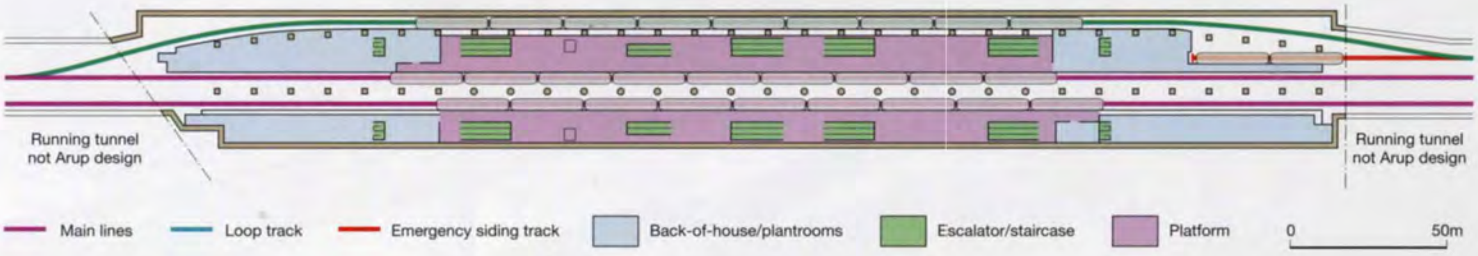
Scope of services

Arup was engaged as sub-consultant to Atkins China Ltd for the station design in 1998, with scope of services including:

- civil, structural, and geotechnical design for the station
- railway alignment design within DD300
- building services design for DD300, excluding system-wide contracts and government-owned facilities
- design for system-wide contract civil/structural interfaces
- design for property development and public transport interchange (PTI) interfaces.

Under the sub-consultancy agreement, Arup was also station design manager, which included co-ordinating architectural, civil, structural, and building services designs, cost control, and railway system-wide interface. The architect was appointed directly by the lead consultant but came under Arup management control for station design and deliverables.

2. Paid concourse level with triple escalators from the ground floor entrance.



3. Platform level plan.

4. The platform extends to over 5m width between escalator/stair zones.

Station planning and architecture

The station was planned to accommodate peak hourly patronage of 36 100 passengers with a maximum of 33 trains/hour in each direction, a projection to be achieved by the year 2016.

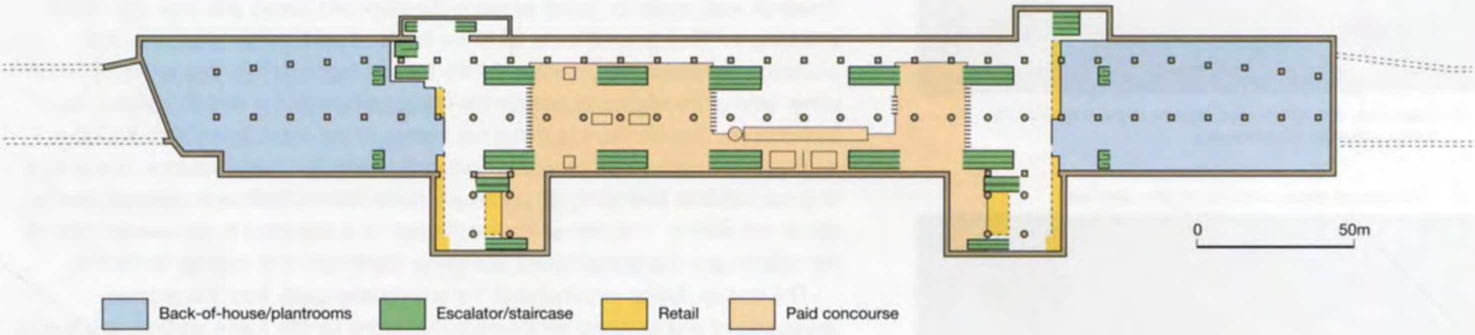
The permanent way design included two through tracks ("up" and "down"), a third loop track running through the station after diverging from the up and down tracks within the transition tunnels, and a short emergency siding (Fig 3). The loop track allows a defective train to be sidelined without unduly affecting overall operations, where a narrow emergency platform is provided for de-training passengers. Once operational considerations had been taken into account, the precise alignment of the railway tracks within the DD300 section was defined by the station planning requirements, which in turn were influenced by economic factors as well as operational needs.

The optimal overall width of the station was achieved by placing the up and down tracks on either side of a central dividing wall, served by two side-platforms. The loop track was located along the western side of the station box, sharing a platform with the up track but separated by a wall with emergency doors for de-training passengers into the main platform area (Fig 4).

The station concourse (Figs 5, 6) is below ground level at the middle of the station, with its entrances strategically placed to integrate with the PTI and future property development. The main entrance (Fig 7) is at the south-east corner of the station footprint and serves the nearby public ferry pier, vehicle drop-off area, and public open space that has been created next to the station. The platforms are below concourse level and are served by 10 paired flights of escalators and staircases connecting to the concourse level, five to each platform (Fig 8).

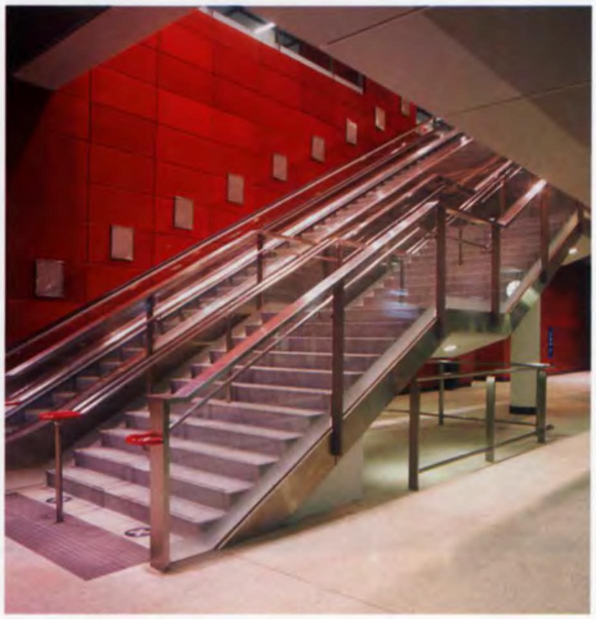
The system-wide equipment and other plantrooms (Fig 9), including control rooms and the tunnel ventilation fan rooms, are in the back-of-house (BOH) areas at both ends of the concourse and platforms . The above-ground structure also includes BOH facilities such as the environmental control system plantrooms, electrical rooms, a loading bay, and transformer rooms.

5. The concourse level, showing columns designed to carry future property development above the station.



6. Concourse level plan.

7. The main station entrance.

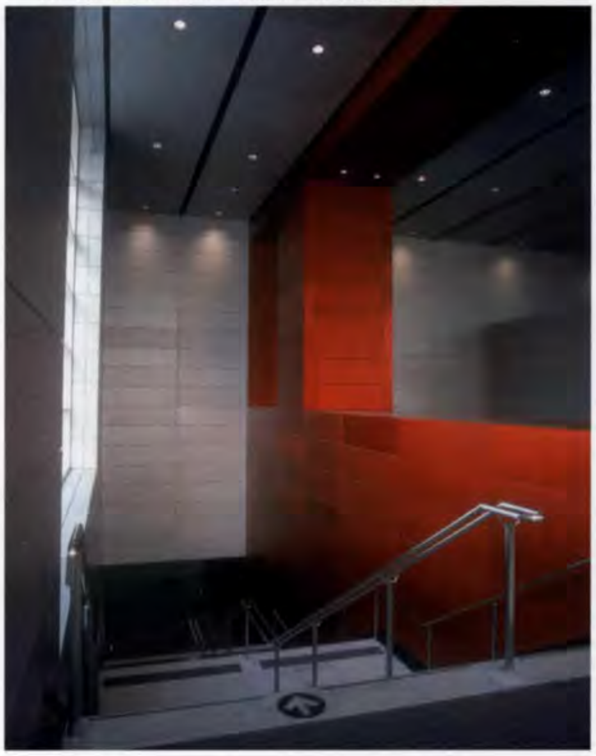


8. Paired escalator and stairs.

9. Tunnel ventilation plant.

10. View from the north-west; façade to be enclosed by future property development.

11. The internal colour scheme of grey and red.



Exhaust air and smoke extraction for the tunnel ventilation system are routed through over-track exhaust ducts above the three tracks along the soffit of the concourse level structure. Fresh air supply comes through under-platform supply ducts in the space between the top of the base slab and the platform level. Both duct systems connect to the tunnel ventilation fan rooms via large concrete air plenums in the BOH areas to the above-ground ventilation shafts.

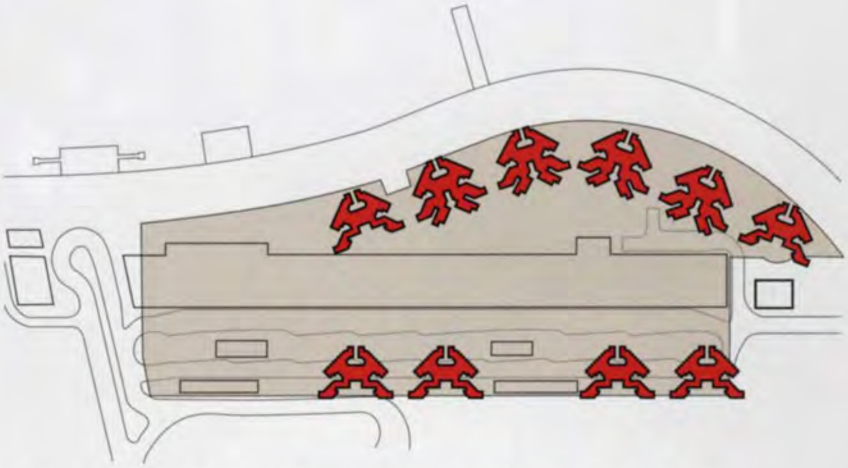
Four groups of ventilation shafts (Fig 10) handle the air supply and exhaust demands for the station and tunnels: two, at the north and south ends of the station, serve the tunnel ventilation system, and two the environmental control system, extending above the first floor level plantrooms midway along the station's length. Where the shafts are within the area of the future property development, they extend to 15m above the top of the future podium level.

The station's external finishes include large areas of exposed boardmarked concrete that the future development will eventually cover (Fig 10). With the prominent ventilation shafts, this currently gives the station a distinctive angular appearance. The surfaces that will remain to view are clad in grey aluminium panels with ground level entrances enclosed in steel and glass. Internally, walls are covered by either grey or deep red anodized aluminium or vitreous enamel-coated steel panels (Fig 11) that reflect the grey of the exterior and the red of the KCRC logo displayed prominently on the sides of the station building.

Property development

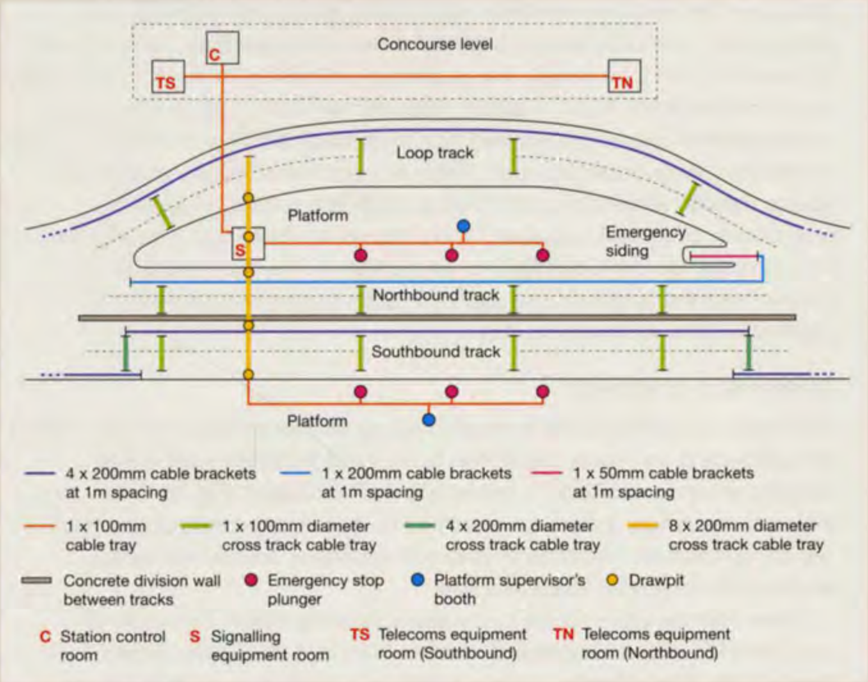
Provision was made for future property development above and near the station, including a PTI at ground level, up to six levels of podium development, and 10 residential tower blocks some 35-45 storeys high (Fig 12). The latter will be on either side of the station to reduce the loads carried by the station columns and foundations. The decision to place the towers to the sides arose from the value engineering exercise carried out in connection with the change from a 12-car to a nine-car scheme (see p24), as previously some towers had been planned directly above the station. This relocation contributed to a reduction in the overall width of the station and foundation loads, achieving significant cost savings for KCRC.

The station design incorporated the anticipated loads from the property development and included structural connections for the future podium and towers. For operational reasons, the first level of podium structure and the ground-level PTI were completed in time for the station opening. With the station and PTI areas roofed over, construction for the future property may proceed without impact on the operation of the railway and other transport facilities.

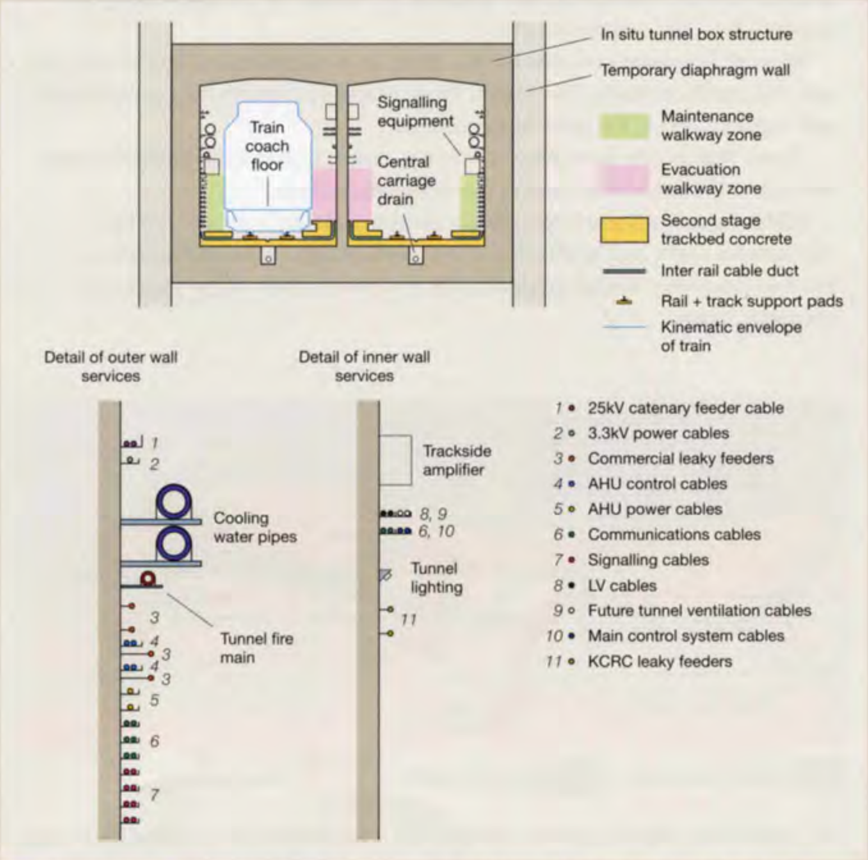


12. Ground floor plan showing locations of proposed residential tower blocks.

Station and approach tunnels: system-wide services integration



13. Typical cable containment schematic for signalling system.



14. Typical cross-section showing services in the cut-and-cover portions of approach tunnels.

Arup's role on this project included design of the electrical and mechanical (E&M) services systems in the approach tunnels as well as for the station itself. This involved many interfaces with the railway systems, including contracts for escalators, lifts, tunnel ventilation, station signs and advertising panels, train control and signalling, traction power and overhead line, telecommunications, main control system, commercial communication, automatic revenue collection, platform screen doors, and permanent way.

The interfaces can be broadly grouped under the following categories:

Architectural provisions: including the control room, space for accommodating special equipment such as ticketing gates and ticketing machines in the station, and niches for air-handling units for tunnel cooling and traction power supply equipment in the tunnels.

Structural provisions: including the structural supports for railway system equipment such as hanger walls for the platform screen doors and support for CCTV cameras.

E&M provisions: including control/ equipment rooms, power supply for equipment outside these rooms, and cable containment throughout the station as well as the tunnels.

Traditionally, these interface requirements are summarized in room data sheets and interface schedules. It had, however, been difficult to define the requirements of the cable containment only in words, particularly when the station layout was still undergoing changes during the design development stage, and so Arup introduced the concept of a schematic layout that defined the cable containment requirements among rooms (Fig 13).

This greatly improved communications between the station/tunnel design team and the railway system designers on the exact requirements of the cable containment systems without the need to wait for the final architectural layout. KCRC realized the advantage of this approach and subsequently included these diagrams as part of their standard interface specifications for future projects.

Co-ordinating the E&M services in the tunnels was another challenge. Tunnel size is normally dictated by the trains' kinematic envelope as well as the services zone required around trains for installing the associated E&M services, including the cable containment for the railway systems. Thus, there is always pressure to minimize the services zone and hence reduce the tunnel cross-section, which in turn helps to reduce construction cost. This requires identification of the needs of each railway system as well as careful planning of the routing and the location of the services in the tunnels (Fig 14).

15. Southern transformer building.

Structure

The station is of conventional reinforced concrete construction with up to two levels of above-ground structure in some zones over a 391m long x 43.2m wide below-ground station box. Track level is some 16m below final ground level, giving an overall excavation depth of around 18m from the initial reclamation level.

Columns are typically at 12m spacing along the station length. Two columns are adopted across the station with two 17.4m spans above the up and down tracks and a 7.2m span over the loop track. Columns within public areas are generally circular to aid passenger circulation, whilst in the BOH areas rectangular sections are used.

Solid flat slabs were adopted for both the track and platform slabs, whilst traditional beam-and-slab construction was preferred for the concourse and ground-level structure to allow for the large openings needed for staircases, escalators, services ducts, and shafts.

Separate transformer buildings were required at each end of the station box, KCRC requiring them above ground to simplify future maintenance, removal, and replacement, and to ensure they are flood-proof. For planning reasons the southern building, which also houses ventilation shafts (Fig 15), is supported directly off the station structure whereas the northern building is slightly beyond the end of the station box above the approach tunnels, which are some 9m below ground. The two-storey structure stands on a solid slab raft foundation on compacted soil directly laid over the running tunnel roof slab.

Foundation system

The perimeter of the station box is a diaphragm wall, which functioned as the temporary retaining system during construction and now forms the permanent basement wall. Generally, the walls are 1.2m thick, connecting at the track, concourse, and ground level for lateral support. Along the east side of the concourse there are large escalator voids directly against the perimeter wall, giving a clear 14m span from ground level down to the track slab. Here the wall is increased to 1.5m thick panels. The diaphragm wall panels are taken to rockhead to carry vertical loads from the station itself and the future property development.

Each station column is supported by a single large-diameter bored pile up to 3m in diameter and socketed into rock. These also provide necessary resistance against flotation where the column load is insufficient to balance uplift from groundwater piezometric pressure. Where shallow rockhead was encountered, the foundation system is pad footings integrated with the track slab under each column. Here the tie-down force against flotation is provided by a series of prebored H-piles socketed into rock.

Construction constraints

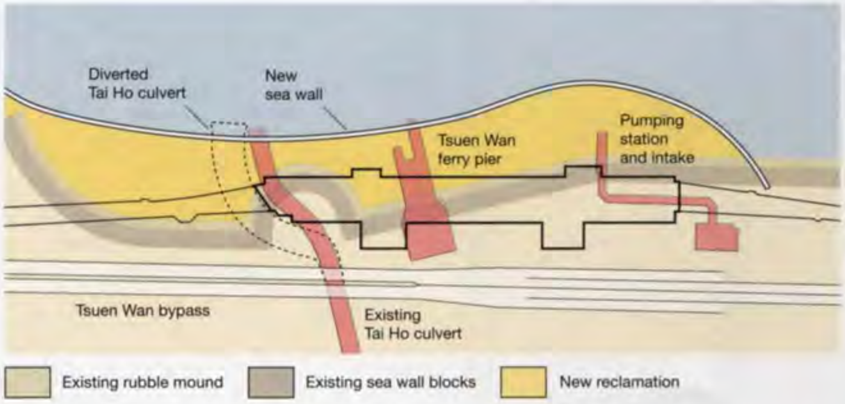
The station is positioned with its western half on land reclaimed in the mid-1980s for constructing the nearby Tsuen Wan bypass and the eastern half in new reclamation carried out under a separate West Rail contract (Fig 16). In the early stages of the design, a thorough search for as-built record drawings was made at relevant government departments to identify existing or abandoned buried structures in the vicinity. These included:

Tsuen Wan bypass - parallel to the east side of the station box some 45m away from the station excavation and about 20m from the nearest entrance adit (Figs 17, 18). During detailed design, geotechnical analysis concluded that the station excavation would cause ground deformation at the bypass piers. Extensive geotechnical instrumentation was specified to monitor deformation during the station excavation and construction.

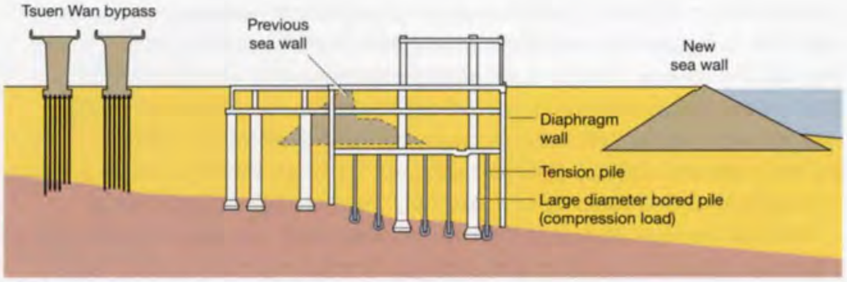
Seawall – massive concrete blocks sitting on a rubble mound and overlapping with the station footprint. Removal of those blocks in conflict with the diaphragm wall was included in the reclamation contract.

Tsuen Wan public ferry pier – within the station footprint, so demolition and removal of the pier formed part of the reclamation works.

Water Supplies Department (WSD) pumping station – about 18m from the station's north end. Monitoring points were installed to record ground and building movement during excavation for and construction of the station and approach tunnel.



16. Location plan showing earlier sea defences and reclaimed land prior to station construction.



17. Overall cross-section through Tsuen Wan bypass and reclamation.

18. The Tsuen Wan bypass elevated highway runs along the north-east side of the site. The risk of the excavation works causing excessive ground movements that might affect the structure were mitigated at design stage by the choice of preloaded struts and by adjusting the railway alignment to bring the structure outside the zone of influence of the excavation.

Seawater intake pipes to the WSD pumping station - alignment clashing with the station footprint so agreement with WSD to re-align was needed. The reprovision work was sequenced so as not to affect operation of the pumping station.

Tai Ho stormwater culvert – cutting across the station footprint. At the 12-car scheme stage this could only be diverted across the BOH facilities at the southern end of the station, creating difficulties with the station planning and construction sequence. Changing to a nine-car scheme reduced the station length from 570m to 391m, allowing the culvert to be diverted beyond the south end of the station box and allowing significant improvements in the design both in terms of increased headroom in the BOH and simplified construction.

Construction programme

The contract period ran from September 1999 to November 2003, the works being managed through a series of 18 key dates for handover of areas between the project and system-wide contractors. These ranged from initial handover of site areas after completion of the reclamation in early 2000 through to handover for track installation in January 2002 and completion of all civil works by July 2002 (Fig 20 overleaf).

Station construction

Tsuen Wan reclamation contract CC302 was awarded to the Sino-European joint venture in March 1999. The works included site reclamation, provision for diverting and extending three large multicelled box culverts, construction of a new seawall, and demolition and removal of various structures including the WSD pumping station intake pipes and the existing Tsuen Wan ferry pier. Particular attention was given to removing obstructions within the station box footprint, as this would have been very difficult once the CC300 works began.

Contract CC300 for the station and approach tunnels was awarded in September 1999. Starting the station works was governed by the dates for handover of the site from the CC302 contractor, and so the station box excavation was split into three working areas (SB1, SB2, and SB3).

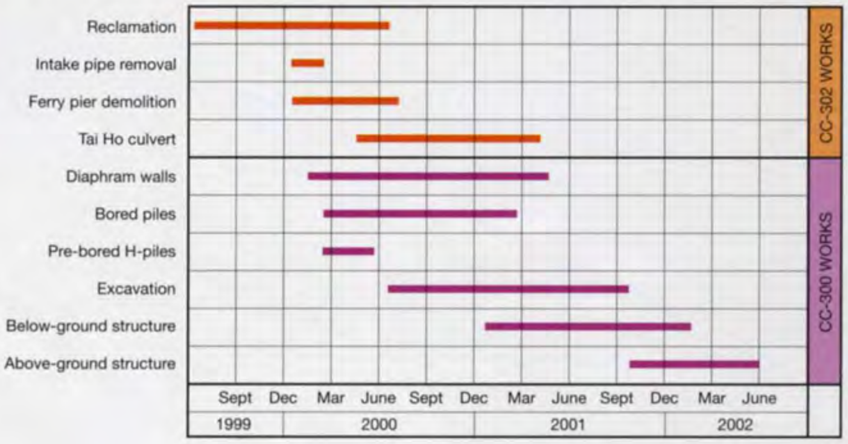
19. Underpinning of diaphragm wall panels.

Permanent diaphragm wall and piling works began at the north end of the station box (SB3) in January 2000, whilst demolition of the ferry pier and reclamation continued at the south. The rubble mound left over from removal of the sea wall across the line of the diaphragm walls had to be sealed into a bentonite/cement matrix, requiring extensive pretrenching work. Once complete this allowed the traditional diaphragm wall excavation to proceed, excavating down through the improved ground without loss of the bentonite slurry.

During the diaphragm wall construction, the rockhead along a 12m length of it was found to be above the soffit level of the track slab. To avoid chiselling through up to 3m of hard granite using diaphragm wall rigs, the toes of the panels were constructed above the level of the track slab and underpinned. During excavation, a third layer of struts was installed above the toe of the diaphragm wall to maintain its lateral stability, after which excavation continued, using mechanical breakers to remove the rock, down to the eventual underside of the track slab. The diaphragm wall was undermined to half its thickness to allow permanent underpinning in the form of a reinforced concrete upstand wall cast against the rock face to support the vertical and lateral loads from the diaphragm wall above (Fig 19). The surface of the rock excavation was mapped to identify potential weaknesses, and was found to be relatively intact. This meant that face stability was less of a concern and water seepage into the excavation was minimal. Once the track slab and upstand wall had been cast, the props were removed and the construction joints grouted up to prevent any water leakage into the station.

To divide the station box into the three working areas, two rows of temporary bentonite/cement slurry cut-off walls were constructed across the width. Toe grouting was also carried out beneath the diaphragm walls, and the combination of grouting and slurry wall formed an effective cut-off against groundwater seepage into the excavation. Dewatering was followed by excavation with two layers of preloaded, battened struts supporting the diaphragm walls and a stepped excavation using soil berms to stabilize the temporary slurry cut-off walls. Excavation from zone SB3 then progressed southward by cutting through the soil berms and extending the line of struts as completed sections of diaphragm wall became available.

20. Construction sequence for the civil and structural station works.



21. Installation of the second layer of struts before completion of the 1.5m thick reinforced concrete track slab.

22. North-east elevation of Tsuen Wan West station, with Tsuen Wan bypass in the foreground and Rambler Channel beyond. In the distance is the cable-stayed Ting Kau bridge carrying road traffic into the New Territories to the north, part of the complex of bridges built to handle traffic to and from the new Hong Kong International Airport.

Using only two layers of struts for the 18m deep excavation created an open working area, allowing great flexibility in moving plant and materials within the excavation (Fig 21). The risk of accidental removal of struts was considered at design stage, and further mitigated by adding a third layer of struts at the designated cranage positions for removing muck and delivering materials; this created an extra level of redundancy in the temporary works.

The 600+ individual geotechnical monitoring points included inclinometers in the ground around the excavation and in the diaphragm walls, strain gauges for monitoring the forces in the struts, piezometers, and various types of ground settlement monitors. These were read either manually or downloaded to a real-time monitoring system that generated automatic status reports, comparing the data to predetermined threshold values.

For monitoring the effects of the works on the Tsuen Wan bypass, an automatic deformation monitoring system (ADMS) was set up, comprising three computer-controlled theodolites (total stations) installed along the length of the works, aimed at over 250 reflective targets attached to the bypass deck and piers. For two years, regular inspections of the bypass plus interpretation of the monitoring data allowed the works to proceed uninterrupted and with the confidence that there were no adverse affects on the adjacent structures. ADMS data taken on completion of major construction activities showed that the bypass piers had moved towards the excavation, but within allowable limits.

Site supervision

Site supervision followed the KCRC West Rail arrangement for engineers' design contracts with two teams:

(i) the KCRC construction management working under the project manager

(ii) the resident site staff appointed by the detailed design consultant working under the chief resident engineer.

Significant benefits, notably the readily accessible pool of knowledge, arose from staff continuity in both teams throughout design and construction. Strong leadership from both sides of the site organization helped build an open and co-operative working relationship with the contractor. The positive attitudes of all parties, including the contractor, aided smooth progress and made no problem insurmountable, either in managing information flow to site or from any uncompromising positions being taken in difficult situations.

Conclusion

The design and construction of Tsuen Wan West station was fast track - dictated by a series of interface issues with handover dates designated at the outset of the project. Arup's team exemplified the strength of multidisciplinary working to achieve the key dates and complete the project within budget; the strength of the team was recognized both by KCRC and the JV contractor.

The range of issues involving property development provisions, the adjoining PTI, and in particular the change from a 12-car to nine-car system, made for very interesting challenges. This required a complete revisit of station planning, design issues, construction, and logistics to ensure the project remained within KCRC's timescale.

As it awaits the proposed extensive property development to be constructed above and alongside, as well as other nearby large-scale developments (notably the Nina Tower, for which Arup is also engineering designer), the station is yet to realize a busy throughput of users. When this happens, it will reach its planned potential, an exemplary fully integrated transport and property development project for KCRC.

During land reclamation an old ship's anchor was discovered, and it is now displayed in front of the station entrance facing the harbour (Fig 23). As well as the names of the designers and main contractors involved there is an inscription on the plinth in English and Chinese: "This anchor discovered during reclamation of land for Tsuen Wan West Station, is presented to commemorate the efforts of those involved in the construction process, March 1999 –October 2003".

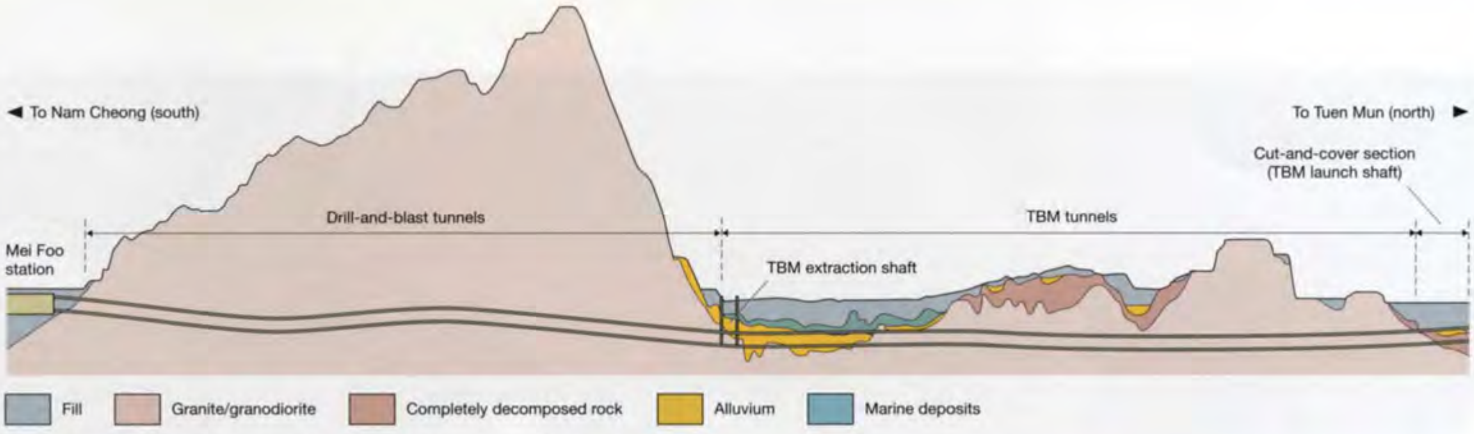
23. Old ship's anchor, newly mounted in front of the entrance.

WH Au is a Director of Arup in Hong Kong. He manages the mechanical and electrical engineering group in Hong Kong and was E&M design leader for the detailed design of Tsuen Wan West station and the associated approach tunnels.

Martin Mok is an Associate of Arup in Hong Kong. He was structural design manager for the detailed design of Tsuen Wan West station and acted as senior resident engineer throughout much of the station construction.

KK Yin is an Associate Director of Arup in Hong Kong. He was geotechnical discipline leader for the comprehensive land and marine ground investigations, and foundation and deep basement design for Tsuen Wan West station.

Richard Scott formerly worked for Arup in Hong Kong. He carried out substructure and foundation design for Tsuen Wan West station and was part of the resident site team for much of the construction period.



1. Long section through the Kwai Tsing tunnels, showing simplified geology.

Kwai Tsing tunnels

Glen Plumbridge

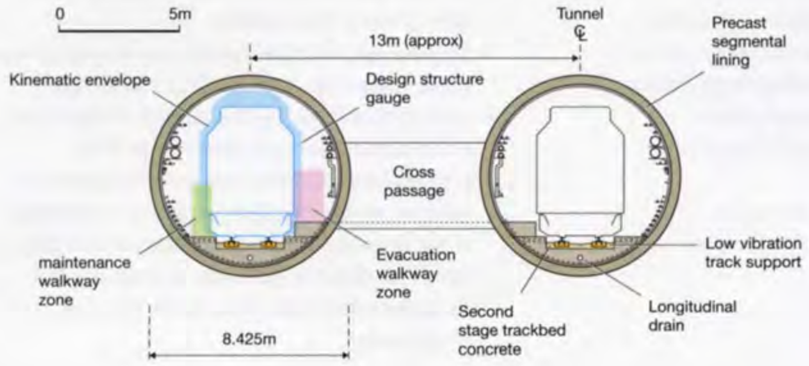
These run between Mei Foo and Tsuen Wan West stations and comprise three sections of twin-track work: the 1.7km long Ha Kwai Chung tunnel, the 1.8km long Tsing Tsuen tunnel, and the 120m long Tsing Tsuen cut-and-cover section that formed the tunnel boring machine (TBM) launch shaft.

Arup was employed as design checker by the Dragages Zen Pacific Joint Venture that was awarded the project in October 1998, procured as with the Tai Lam tunnel (see p23) using the design/build form of contract. Arup's scope of work included checking all the contractor's civil, structural, tunnelling, geotechnical, architectural, mechanical and electrical design including, like Tai Lam, a large ventilation building.

Tsing Tsuen tunnel was the first project in Hong Kong to use a state-of-the art mixed face earth pressure-balanced tunnel TBM. Built by NFM Technologies of France in collaboration with Mitsubishi Heavy Industries of Japan and assembled in Shanghai, the 8.75m diameter TBM was capable of working in a range of conditions from hard rock to soft ground. It was shipped to Hong Kong in early 2000 and successfully completed the two 1.8km bores well within programme. The single bore Ha Kwai Chung tunnel was constructed by traditional drill-and-blast techniques, a practical solution for the solid rock formations found in this section.

All the tunnels include cross-passages at 90m spacing along the route. At Ha Kwai Chung a central dividing wall was introduced, while between the twin-bored TBM tunnels the cross-passages were hand-mined.

2. Typical cross-section through the twin bored Tsing Tsuen tunnel.



Again as for the Tai Lam tunnel contract, Arup's role included detailed checking of the final designs as well as active participation in scheme development with the contractor and his designer, reviewing alternative solutions and methods to ensure cost-effective and timely completion of this section of West Rail. Once more the firm was able to add value to the project by assisting with ideas and solutions to important issues. One key constraint was construction of the cut-and-cover tunnel adjacent to the existing elevated Tsuen Wan bypass (see also pp30-33). This is highly sensitive to lateral movements and significant effort was put into developing a construction sequence that would reduce impacts to an acceptable level.

3. Front shield of TBM in launch shaft.

1. Yuen Long Station platform: sound absorption is by absorbent material behind the perforated ceiling panels.

West Rail stations: acoustic design

Sam Tsoi

Introduction

West Rail is a world-class railway, and world-class railway passenger safety standards were essential for it. Proper acoustic conditioning, with clear and intelligible speech from the public address (PA) system for emergency evacuation was an important requirement, as well as the need for passenger acoustic comfort in the station environment. This lesson was learned after the London King's Cross fire in 1987, where 31 people died at the city's busiest Underground station. The lack of intelligible voice communication is believed to have contributed to the loss of life.

Factors influencing acoustic performance in a station include control of reverberation time (RT), services noise, and sound insulation: all three impact passenger amenity and the speech intelligibility of a PA system.

Arup's involvement in the West Rail acoustic consultancy included:

- system-wide acoustic design strategy for the stations, maintenance centre, and West Rail headquarters building
- detailed architectural acoustic and services noise control designs of Yuen Long, Long Ping, and Tin Shui Wai stations
- detailed architectural acoustic design of Tuen Mun and Siu Hong stations
- detailed services noise control design of Tsuen Wan West station
- RT testing of the concourse and platforms of Kam Sheung Road station
- post-project rail noise impact monitoring of Yuen Long, Long Ping, and Tin Shui Wai stations
- post-project fan noise monitoring of Yuen Long North public transport interchange (PTI)
- implementation of the trackform mitigation and services noise control measures recommended in the Environmental Impact Assessment (EIA) report for stations, viaducts, and associated essential infrastructure works for the Yuen Long section.

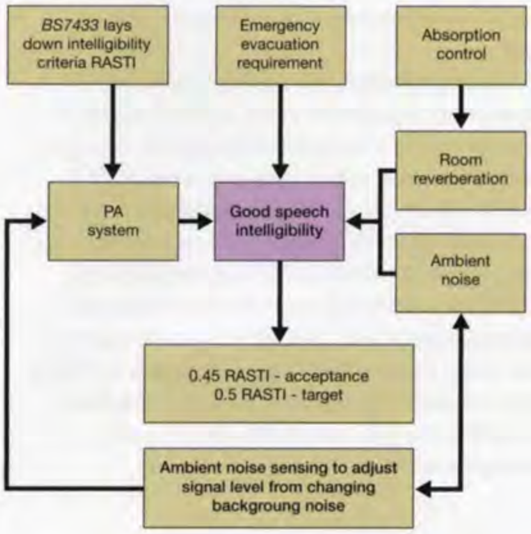
Arup involvement in station system-wide acoustics in Hong Kong started with the MTR Corporation's Lantau and Airport Railway (LAR) in 1993[1], continued through its Tseung Kwan O extension projects, and subsequently to KCRC's West Rail.

Through validation of acoustic prediction methods from compliance testing of acoustic space performance at the commissioning stage of the earlier projects, and experience of managing the implementation of the acoustic strategy in the process, the knowledge gained was applied to the acoustic design and strategy for West Rail. The dual role of system-wide and detailed design consultant also provided an unparalleled opportunity to influence the acoustic design at two levels. Firstly, as system-wide design consultant, Arup developed the strategy and implemented the subsequent verification control framework to ensure the acoustic design requirements would be achieved. Submissions by the detailed design consultants were rigorously reviewed to check and verify compliance against the design objectives.

At this strategic level, system-wide recommendations formed a basic standardized framework to direct the acoustic design development of the individual station designer, and allowed flexibility for progressing their designs to suit specific site constraints and optimization need.

Secondly, as detailed design consultant, Arup advised individual station designers on an integrated aesthetic and acoustic solution and on services noise control. 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 from the air distribution system, and noise and vibration control of E&M plant.

2. PA system design strategy.



3. Acoustic ceiling panels at Tin Shui Wai station.

Acoustic strategy

The acoustic design approach was "target-and-acceptance". 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 to achieve the design intent - criteria that have to be achieved respectively by design prediction and at commissioning. This strategy takes account of uncertainties in the design algorithms and minimizes the impact of any design deviations during construction.

The team developed a complete set of acoustic design target-and-acceptance criteria and implemented the strategy, allowing the use of conventional acoustic prediction methods for the complex acoustic geometry of the station space.

The contract strategy for West Rail was to engage a design/build (DB) contractor for the entire line's PA system. This was contained within contract DB1500 for telecommunications, won by Siemens Ltd. Since both the acoustic design and the PA system design have an impact on speech intelligibility, there were interface issues between the specific acoustic designs of the detailed design consultants and the PA installation of the DB contractor, and a strategy was devised to handle these in the system-wide approach.

Interface between PA system and acoustic design

Background noise level and room acoustics both affect speech intelligibility, for which British Standard *BS7443*[2] defines an objective criterion for PA systems as RASTI (RApid Speech Transmission Index). RT and services noise levels are essential design parameters for speech intelligibility of spaces, and are the relevant criteria for achieving the RASTI requirements, so both the acoustic design and the PA system design have an impact on the RASTI values that would be achieved. Proper interfacing between the room acoustics and the PA system is therefore important to acoustic design success and the safety of the completed stations, and the standards achieved are the subject of a contractual constraint (Fig 2).

The recommended target-and-acceptance RASTI values for the West Rail stations were 0.5 and 0.45 respectively, based on a minimum signal-to-noise ratio of +15dB. The PA system contractor was responsible for meeting the specified RASTI value based on the acceptance RT and services noise criteria, and thus needed to develop the form and function of the PA specific design details. The station design teams provided the background noise levels, the room acoustics of the spaces, and the RT as baselines to enable the PA system contractor to prepare the design and installation.

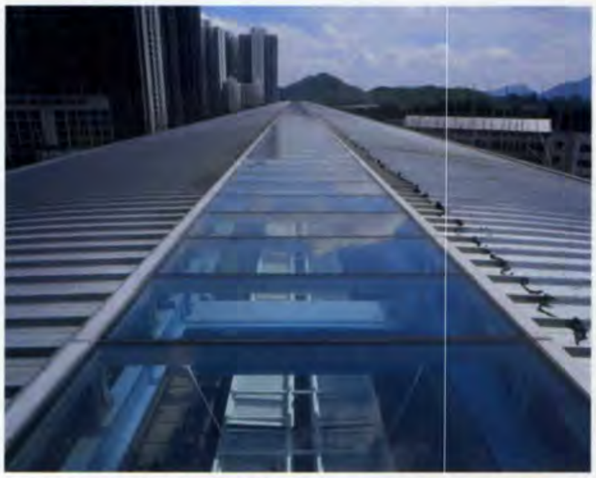
Room acoustic response prediction

One major objective of the architectural acoustic design was to predict the RT in a given room space. At that time, there were no published standardized methods for RT design prediction although several academic prediction methods existed for theoretical acoustic analysis. Most were relatively simple equations, applicable for spaces of a reasonable proportional geometry. For example, Sabine's classical equation (named after a 19th century Boston academic who pioneered scientific acoustic design) is still one of the most widely recognized methods and was generally adopted for RT prediction. For a long enclosure, the more complex "Kang/Orlowski"[3] calculation method was also proposed in some designs, though it was not yet fully validated by actual field measurements.

The volume of space, the surface areas of various material finishes, and their absorption coefficients, were key input parameters for analysis, but in practice the assumption of diffuse sound field conditions for applying Sabine's theory deviates from reality. Public areas in transportation buildings, for example, fall outside this category.

The disproportionate spaces of train platforms and concourses could introduce uncertainties in prediction when using conventional methods.

It was necessary, therefore, to take into account this tolerance in design to ensure that the ultimate targets were achieved. A simple approach to RT design was therefore to adopt the target-and-acceptance strategy. The upper and lower bound values were narrowed through experience gained from previous projects.



4. Metal roof at Tin Shui Wai station, minimizing road traffic noise intrusion.

5. Acoustic ceiling panel at Long Ping station.

EIA noise legislation and services noise control assessment

All fixed plant noise sources at West Rail have to comply with environmental noise standards in accordance with the EIA Report, and this applies not only to the functional spaces of the stations, but also to external noise-sensitive receiver locations. The noise criteria should not be exceeded by the simultaneous operation of all E&M building services, including regenerated aerodynamic noise, breakout noise, and structure-borne and airborne noise. The earlier the noise control requirements were addressed in the design, the more likely that these requirements could be fulfilled economically and straightforwardly. Again, the target-and-acceptance strategy was adopted.

The external noise-sensitive locations included both existing and future developments, which imposed a flexibility requirement in the acoustic design to manage the changes without adverse impact on project programme and budget. As detailed design consultant, Arup developed a technique for control of duct-borne noise from multiple sources. It was based on the concept of equivalent near-field noise limit derived for each of the E&M ventilation and exhaust louvres in the EIA report to account for the total number of contributing noise sources in the services noise control design. The benefit of this approach lies in its simplicity to incorporate the precise acoustic requirements into the contracts and the ease of management control for changes during construction or commissioning at project completion. The acoustic requirements were transferred to a set of equipment-based performance standards, enabling the M&E contractor easily to select equipment to meet the acoustic requirements.

Services noise control design is a source-path-receiver analysis, and this is subjected to influence of all components in the system including ducts, plenums, fans, diffusers, grilles, etc. An automated calculation spreadsheet program was developed to enable a large amount of air-handling unit and fan noise calculations to be prepared as the design was being refined. The most important elements in the acoustic design are to control the emitted sound power levels and the regenerated noise; these are affected by proper selection of sound attenuation devices and by limiting duct velocities. Noise control design for major plant items like chillers and transformers was also developed.

Construction and acoustic testing

The stations vary considerably, but certain key features were common linewide. All concourses and platforms had absorption to the ceilings, in some cases behind perforated metal tiles/panels. In some concourse areas, additional absorption was provided in the form of acoustic plaster sprays on the ceiling soffit to conform with the aesthetics of the architectural design.

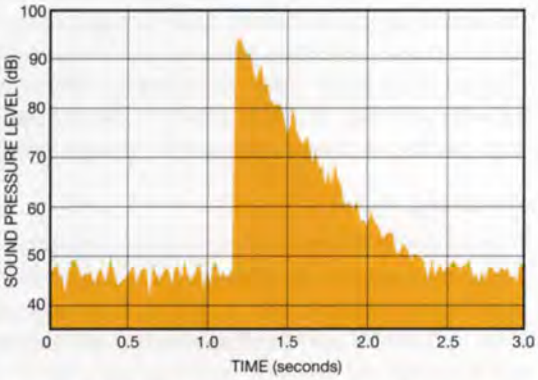
An impulsive noise source method was adopted to measure RT. A large balloon burst at the selected source location created a loud impulse whose sound decays were measured by a modular PC-based system (Harmonie) with receiving microphones at 5m, 10m, and 15m away from the source. The four-channel real-time analyzer comprises hardware resource, software modules ,and a host computer. Time history of the decay sound was captured and RTs were analyzed in octave bands from 125Hz to 4kHz (Figs 6, 7).

Services noise measurements were conducted with all the services plant set to normal operation mode.

Conclusion

Previous RT testing and services noise measurements from the LAR stations confirmed that the LAR had achieved very high standards. The same RT testing and service noise measurements at the Tseung Kwan O Extension stations indicated compliance with the criteria specified for its acoustic control programme, at a higher confidence level of design and lower acoustic control budget. West Rail is now running, successfully incorporating all this previous experience. The tremendous experience and knowledge gained on these projects will benefit the next generation of station acoustic design where more complex geometry, space forms, and functional integration and interaction will be demanded without limiting creativity.

6. Acoustic RT testing at Kam Sheung Road station.



7. Typical decay history for the impulsive source.

8. Acoustic panels on the parapet.

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References

(1) TSOI, S. The acoustic design: Terminal Building and MTRC stations. *The Arup Journal*, *34*(1), pp32-33, 1/1999.

(2) BRITISH STANDARDS INSTITUTION. *BS7443*. Specification for sound systems for emergency purposes. BSI, 1991.

(3) KANG, J *and* ORLOWSKI, R J. Reverberation in rectangular long enclosures with diffusely reflecting boundaries. Joint Meeting of the 137th Regular Meeting of the Acoustical Society of America, the 2nd Convention of the European Acoustics Association (EAA) (Forum Acusticum), and the 25th German Acoustics DAGA Conference, Berlin, Germany. Also published in *Acustica/acta acustica*, *85*, pp389-390, 1999, and *Journal of the Acoustic Society of America*, *105*, pp1315-1316, 1999.

(4) TSOI, S *and* NG, W. Speech intelligibility design of PA system in transportation buildings. The Hong Kong Polytechnic University Symposium 2001: New challenges in building acoustics, Hong Kong, 2001.

(5) NG, W *and* TSOI, S. Acoustic audits of the Lantau and Airport Railway stations. Proceedings of the 8th International Congress on Sound and Vibration, Hong Kong, 2-6 July 2001, pp829-836.

(6) NG, W *and* TSOI, S. Tseung Kwan O extension consultancy agreement No 6007: Systemwide acoustic audit and close-out report. Arup Acoustics Report *22558-16*, 2002.

West Rail advance pile test study

Stephen Hill Glen Plumbridge

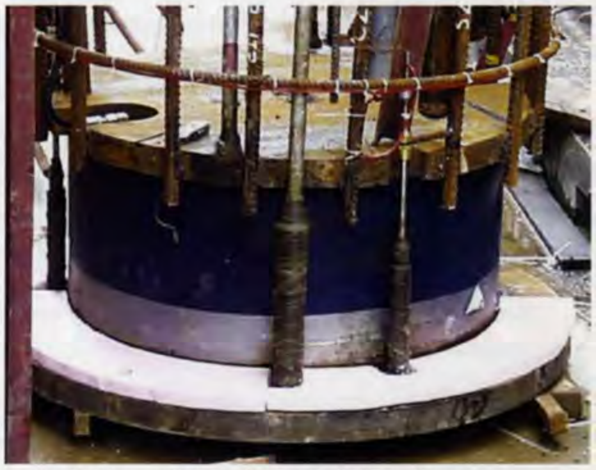
Introduction

With some 13km of viaduct and nine stations all requiring some form of piled foundations, thousands of piles of differing lengths clearly would be needed. Significant economies could be gained if the prescriptive pile capacities laid down in the Hong Kong Building Regulations could be enhanced, and Arup was commissioned to design and supervise a test pile programme. Costing HK$100M, this was on an unprecedented scale for Hong Kong. With the Building Regulations' design approach adopting presumptive bearing capacity on rock of up to 7.5MPa, Arup set out to adopt higher capacities for use in a rational design. In addition, for areas with deep rockhead proven in places to exceed 100m, the innovative shaft grouting technique was used to enhance friction capacities.

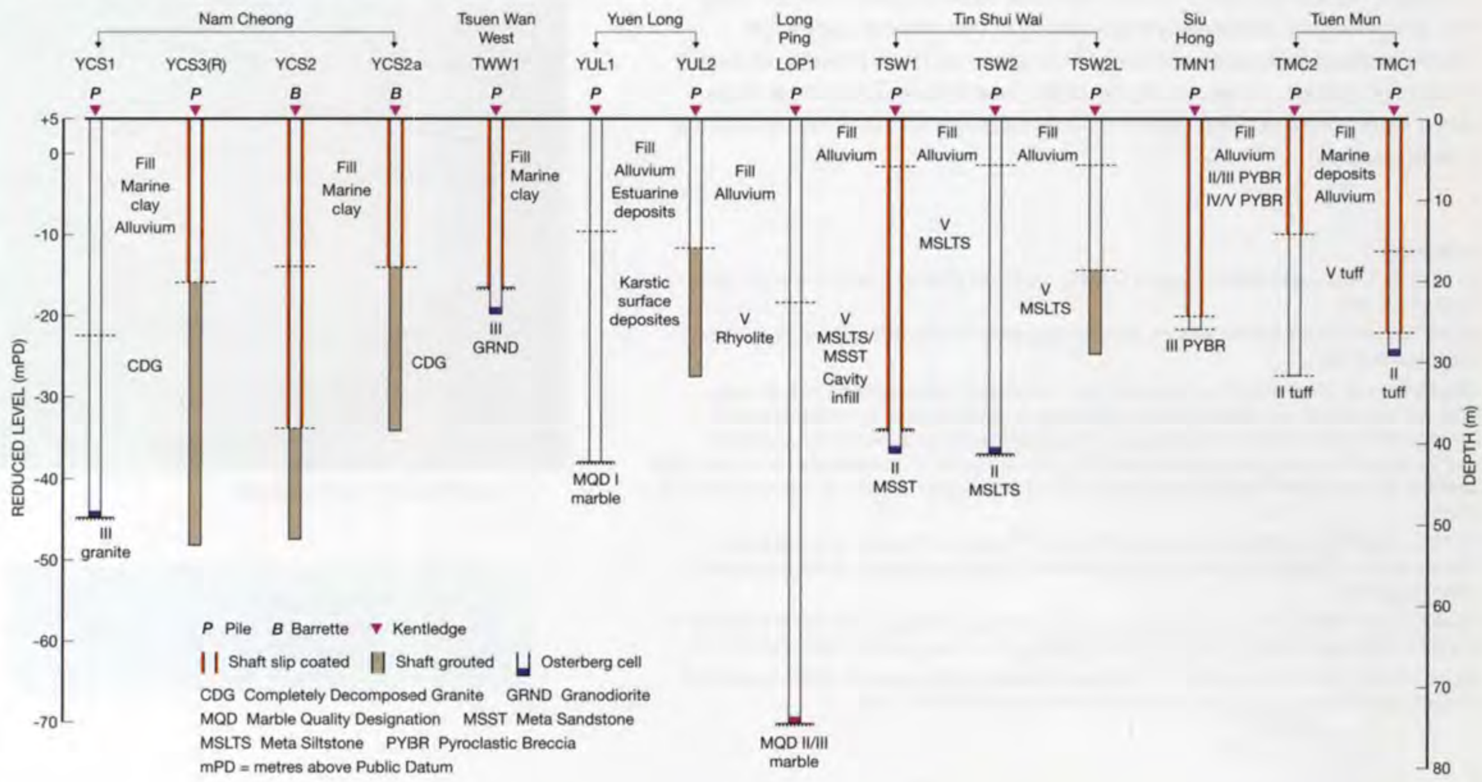
The testing regime

To meet the programme's objectives, Arup designed it to maximize the test data. Twelve piles and two barrettes were load-tested to a maximum of 30MN; the piles were 30-73m long and 1.2m and 1.5m in diameter, whilst the barrette sizes were 2.8m by 0.8m. All were fully instrumented and included vibrating wire strain gauges and retrievable vibrating wire extensometers (Fig 1).

To test piles bearing on rock, six were constructed with 865mm diameter Osterberg cells at the toe. Even with this advanced technological testing, the combined load case of rock socket and end bearing had to be proven for the Hong Kong Government Buildings Department. First, the pile head was loaded with kentledge, and then maximum bearing capacity was achieved by pressurizing the Osterberg cell to 30MN to apply a bi-directional load at the pile toe and directly test the rock. All six Osterberg cells operated successfully, achieving their maximum or close to maximum capacity (Fig 2).



2. Osterberg cell in position at the bottom of a pile reinforcement cage.



1. Summary of vertical pile load test programme.

3. Lateral load test on pile groups.

Shaft-grouted barrettes

Arup introduced shaft grouting on full-scale foundations to Hong Kong in 1998 on a test barrette, where two 30MN Osterberg cells were cast mid-shaft of the 2.8m x 1.5m shaft-grouted barrette. From this test Arup further developed the technique for West Rail, whereby the concrete was first cracked and then injected with a cement grout at the soil-concrete interface using the *Tube-á-Manchette* method.

Ground investigations

As well as the pile tests, a range of innovative ground investigation techniques were used to correlate in situ modulus with that determined from the pile load tests. These included the Goodman Jack (a borehole tool used for estimating the deformability of rock masses in situ), high pressuremeter/dilatometer, self-boring pressuremeter, and crosshole geophysics, in addition to the usual Hong Kong practice of in situ testing during borings.

Lateral load tests

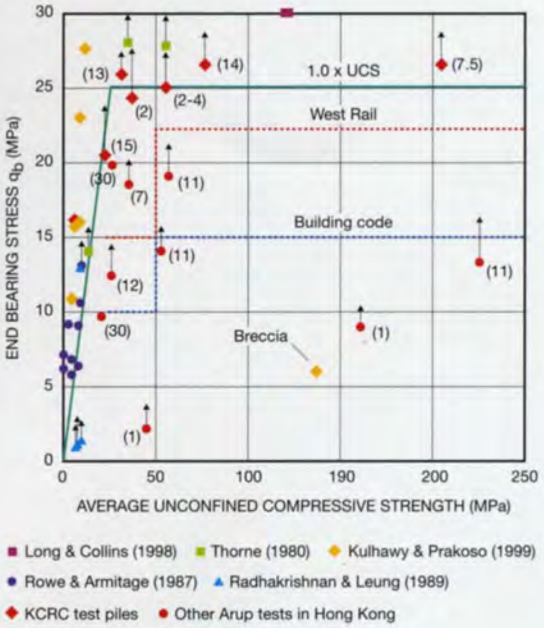
For elevated rail viaduct structures Arup recognized the benefits that lateral pile tests may have for KCRC, and a schedule of lateral pile and barrette tests was incorporated into the programme. Cyclic and maintained lateral load tests were carried out on four single piles and barrettes, as well as a two-pile group and a three-pile group (Fig 3). In addition, a pile group constructed on 2-D and 3-D spacing was tested in a similar manner. The results showed that a two-to-three-fold increase in soil stiffness could be realized above typical design values.

Results

As a result of this testing programme, on West Rail Arup successfully achieved:

- bearing capacities 50% higher than normally adopted presumptive bearing values for use in a rational design (Fig 4)
- approval to use shaft grouting and the enhanced shaft friction capacities associated with it; this aspect of the testing programme achieved a two-fold increase in friction capacities
- justification of higher ground stiffness parameters than normal prescriptive values for laterally loaded piles.

Recognition of these test results by the Hong Kong Buildings Department has resulted in promotion of the use of shaft grouting outside the rail industry in Hong Kong, with the most notable recent project being the foundations for what will be Hong Kong's tallest building, the 484m International Commerce Centre at the MTR Corporation's Kowloon Station property development.



4. Summary of end-bearing test results.

5. De-bonding liner to barrette test.

Stephen Hill formerly worked for Arup as an Associate in the Hong Kong office, specializing in low and renewable energy design.

West Rail consultants and contractors

Detailed design contract DD200: Yuen Long section (pp7-19)

Client: Kowloon-Canton Railway Corporation **Lead consultant, all engineering design, and viaduct quantity surveyor:** Arup **Sub-consultants to Arup** - *Station architect:* Rocco Design Ltd *Viaduct architect:* WilkinsonEyre Architects *Landscape architect:* Urbis Ltd *Station quantity surveyor:* Widnell Ltd **Contractors** - *Kam Sheung Road to Tin Shui Wai viaduct (CC201)* and *Tin Shui Wai to Siu Hong viaduct (CC211):* Maeda-Chun Wo Joint Venture; *Yuen Long and Long Ping stations (CC202):* AMEC-HK Construction Joint Venture; *Tin Shui Wai station and LRT viaduct (CC203):* Chun Wo-Fujita-Henryvicy Joint Venture; *Light rail civil works, permanent way, traction power, and overhead line (CC230):* Leighton Contractors (Asia) Ltd.

Design-build contract DB350: Tai Lam tunnel (p23)

Promoter: Kowloon-Canton Railway Corporation **Client/Design-build contractor:** Nishimatsu- Dragages Joint Venture **Client's independent checking engineer:** Arup **Client's designer:** Maunsell Consultants Asia Ltd.

Detailed design contract DD300: Tsuen Wan section (pp25-34)

Client: Kowloon-Canton Railway Corporation **Lead consultant:** Atkins China Ltd **Civil, geotechnical, SMEP engineer, and design manager for station and MEP designer for approach tunnels:** Arup **Quantity surveyor:** Widnell Ltd **Contractors** - *Station and approach tunnels (CC300)* Penta-Ocean-Kier Joint Venture; *Specialist foundation sub-contractor:* Bachy Soletanche Group – IP Foundations Joint Venture; *Tsuen Wan reclamation contract (CC302):* Sino-European Joint Venture.

Design-build contract DB320: Kwai Tsing tunnels (p35)

Promoter: Kowloon-Canton Railway Corporation **Client/Design-build contractor:** Dragages-Zen Pacific Joint Venture **Client's independent checking engineer:** Arup **Client's designer:** Atkins China Ltd

Advance pile test study (pp40-41)

Client: Kowloon-Canton Railway Corporation **Consultant:** Arup **Contractors** - *Nam Cheong and Tsuen Wan West stations:* Bachy Soletanche Group *Tuen Mun and Siu Hong stations:* The Express Builders Co Ltd *Yuen Long, Long Ping, and Tin Shui Wai stations:* Gammon Construction Ltd

Illustrations:

Photos: Colin Wade **Graphics:** Nigel Whale *with the following exceptions:* ***p3:*** Photo of Andrew Chan, Thomas Graham ***pp4-5:*** 1 Kowloon-Canton Railway Corporation 2 Kenny Ip 3 Damon Yuen/Bird Wong/Nigel Whale ***p6:*** Map, Damon Yuen/Bird Wong/Nigel Whale ***pp7-17:*** 2 Damon Yuen/Bird Wong/Nigel Whale 3, 5 Arup/Nigel Whale 12, 14 WilkinsonEyre Architects 13 Robert Benaim & Associates 15, 16 Rocco Design Ltd 18, 27 Kenny Ip 21 Ka Fai Yung ***pp20-22:*** 1 Arup 5 Jeffrey Lo ***p23:*** 1 Nishimatsu- Dragages JV ***pp25-34:*** 18 Penta-Ocean-Kier JV 21 Arup ***p35:*** 3 Dragages-Zen Pacific JV ***pp36-39:*** 1, 3-5 Kenny Ip 6 William Ng ***pp40-41:*** 2, 3, 5 Arup.

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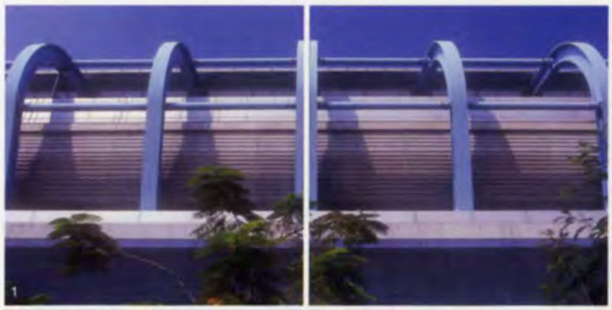
To celebrate its 60th anniversary, Arup is partnering with the international charity WaterAid in a new initiative, The Arup Cause, which focuses Arup's mission to "shape a better world" on the provision of safe domestic water, sanitation, and hygiene education to the world's poorest people.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Illustrations: 1. Tin Shui Wai station; 2. Tsuen Wan West station; 3. Platform level at Tin Shui Wai station; 4, 5. Yuen Long station; 6. Yuen Long Section viaduct piers; 7. Viaduct near Yuen Long station; 8. Distinctive grey and red colour scheme at Tsuen Wan West station; 9. Light rail car beside Tin Shui Wai station.

Front cover: Tin Shui Wai station, with the 14th century Tsui Shing Lau pagoda in the foreground; Inside front cover: Viaduct at the Kam Tin River crossing; P42: Entrance to Tsuen Wan West station at night.

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