



1. Long viaduct spans across the Kam Tin River.

# The Yuen Long section: viaducts and stations

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## Introduction

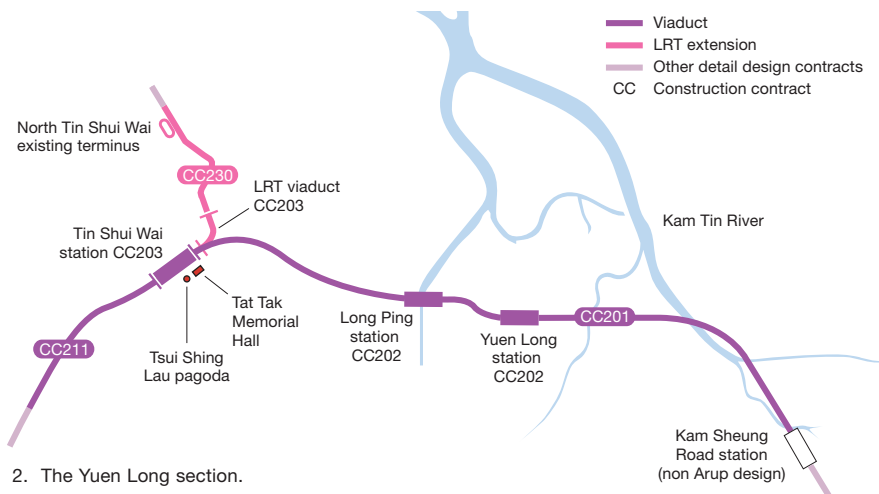
The Yuen Long section, the largest single design package on West Rail, is 8.8km long. A viaduct comprises 7.6km of this length, the remainder being the three elevated stations at Yuen Long, Long Ping, and Tin Shui Wai (Fig 2).

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<sup>1</sup> 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.

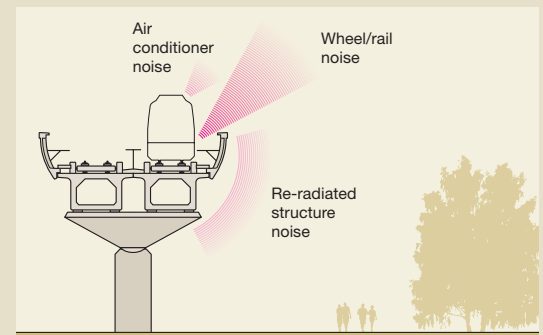
The design of the stations and viaduct was most influenced by the Hong Kong Noise Control Ordinance (NCO), instituted in the early 1990s, which sets statutory noise limits on the operation of railways and other sources. At night (2300 - 0700), operational noise levels along sections of the West Rail 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).

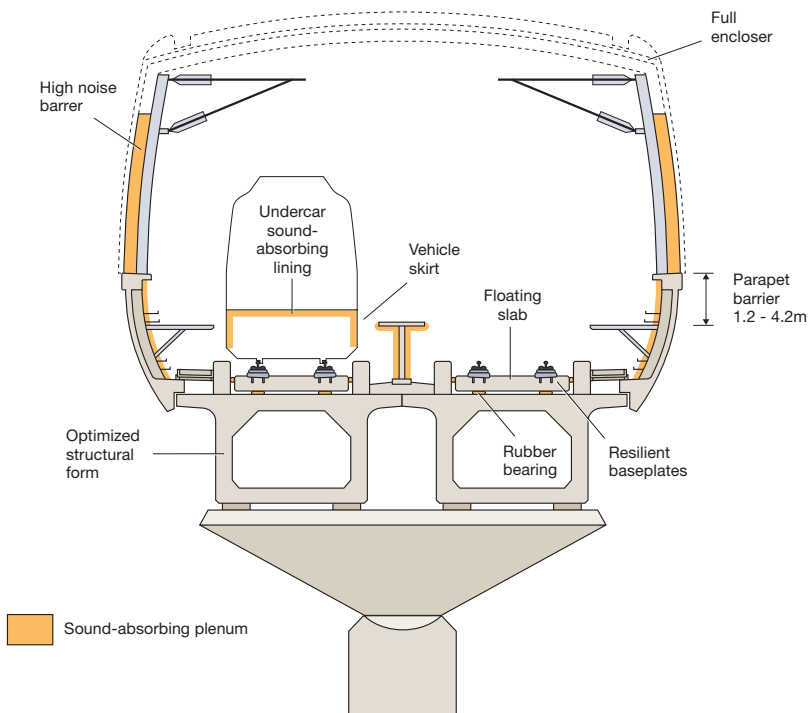
If (3) is adequately limited, achieving compliance for total wayside noise requires significant reductions in both (1) and (2) to a maximum level for each of 61dBA.



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 plenum 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.

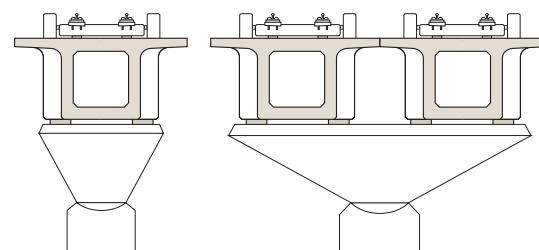
The team developed a structure-borne noise model to predict wayside noise levels and help design development. Starting with a suitable wheel/rail roughness spectrum, vibration levels were calculated in the structure using a finite element analysis, and vibration levels were converted to noise using analytical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

Before making predictions for West Rail, the model was validated against vibration and noise measurement data taken on the MTR Corporation'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.

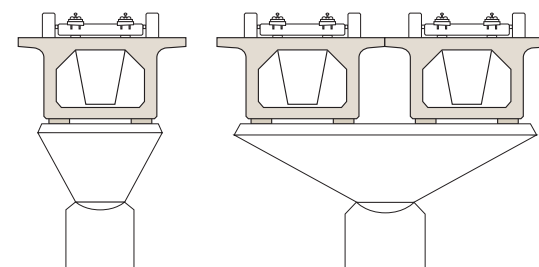
The study considered design variations in type of trackform, mass and stiffness of the section, deck thickness, distribution of mass and stiffness (ie number, size and location of fillets and webs), and noise radiating area. There were two major findings. Firstly, a floating slab trackform (FST) with 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 plenum.

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

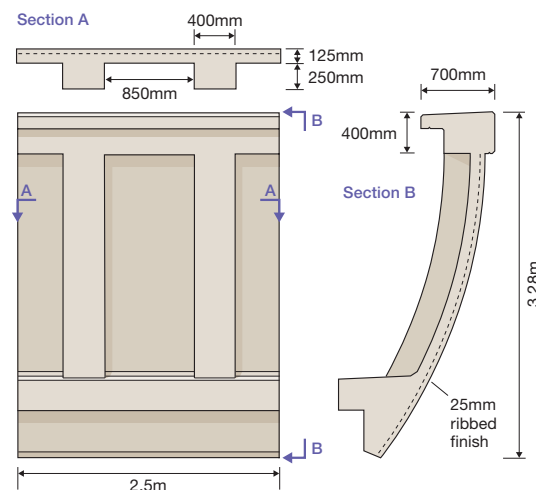


6. Narrow web spacing, with a diaphragm at the pier supports to increase spacing between bearings.



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.

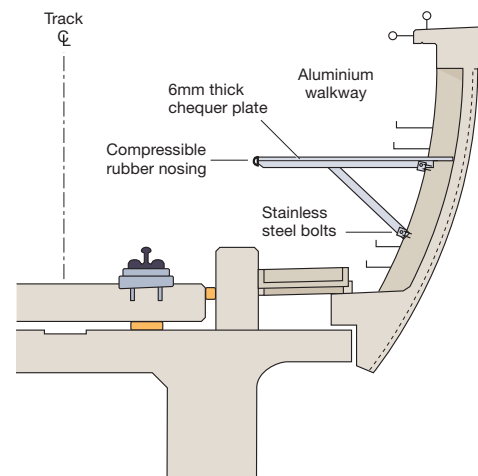
### Superstructure aspects

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 2637<sup>2</sup>.

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.

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.



9. The parapet in use.

### 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.

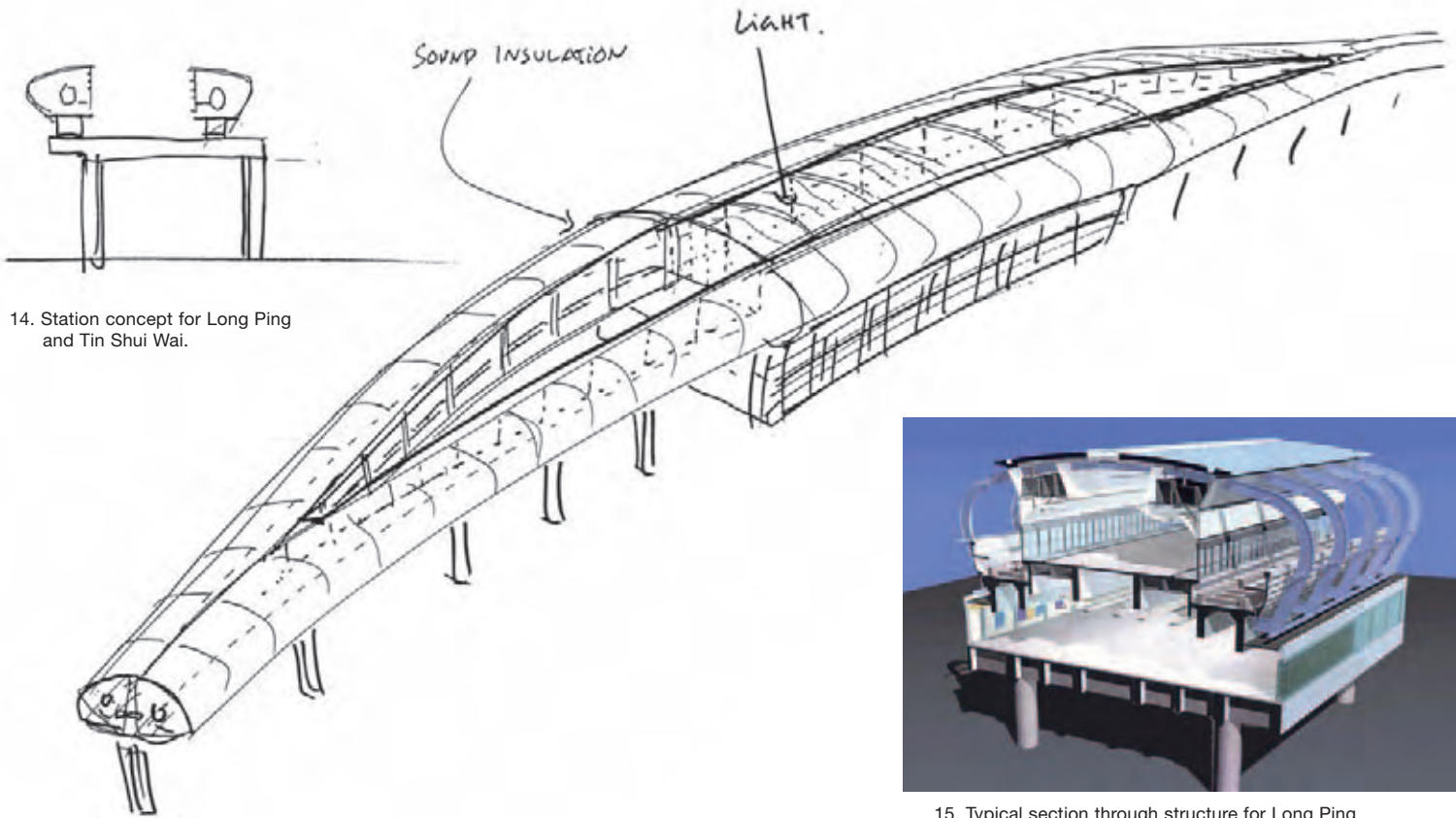


13. Final as-constructed viaduct design.

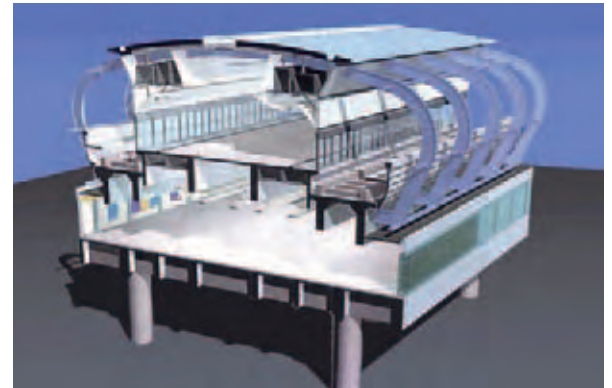
11. The full noise enclosure in use, adjacent to Pok Oi Hospital at Yuen Long.







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



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

## 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.

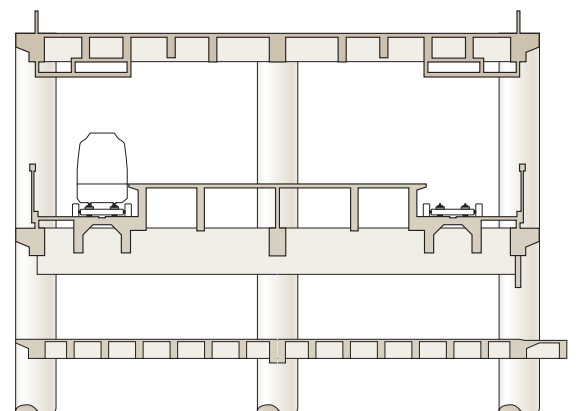
### Design development

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).



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

17. Yuen Long station: cross-section.





18. Central rooflight at Tin Shui Wai station.



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

20. 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.





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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