SYNOPSIS

Planning & Design of Underground Stations in High Density Urban Environment

This paper sets out the key issues facing promoters and designers of mass rapid transit systems (rail based) in highly populated urban environments with case histories from the various cities.

It reviews the planning and design parameters required to make these systems efficient to operate and maintain and how these demands are met by designers and builders in constructing such complex underground structures.

Paper also examines how the requirements of safety of passengers are met and what affect this has on the station layouts.

By

SATPAL S BHOGAL

BSc(Hons) CEng FIStructE FICE

INTRODUCTION

This paper is based on the experiences of the author in Asian cities and recently on the Klang Valley MRT project that is presently under design and construction.

City Centre Scenarios

Over the last three or four decades, rapid development in Asian city centres has left little room to thread rail transit systems through these areas. This, coupled with the need for larger curves needed for railways, poses a major challenge to fit these through the labyrinth of properties that are not only prime commodities of these cities but often extend to considerable depths with underground basements for the parking requirements.

Equally, the depletion of the road reserves, which are the favourite paths sought for by rail transit experts when designing the alignments, to fairly narrow corridors by pressures of the city centre developments, are forcing the designers to go under private properties.

These require going deep or resort to structural solutions of underpinning the existing buildings. Current experience shows that underground rail alignments run at depths ranging from 20 to 30 metres and in places upto 50 metres deep to avoid foundations of existing structures.

Transport Need

The need for public transport systems is taken for granted for the purposes of this paper. It is also taken for granted that the MRT systems have to thread through these high density urban developments with stations located in or among these built up areas, and that the system in the city centre is an underground section . Planning and the need for running the MRT systems underground are not debated in this paper.

This Paper

This paper, therefore, sets out the key issues that need to be overcome in order to meet the functional requirements for the design and construction of underground stations in close proximity of prime developments. The paper uses case histories from other city metros to see how the challenges were met.

TRACK ALIGNMENT

The very first challenge is the design of the horizontal and vertical track alignment. This should satisfy all the requirements of planning and design parameters for an MRT system through heavily built city centre areas. The track alignment is based on tried and tested practices, with mandatory requirements of prevailing minimum parameters.

For horizontal alignment, the desirable minimum track radii = 300m (plain line running track); absolute minimum track radii = 200m (plain line running track); exceptional minimum track radii = 150m (plain line running track) normally applies.

Same applies to the vertical alignment, with desirable maximum running line vertical gradient = 3.0% and absolute maximum running line vertical gradient = 4.0%.

The primary exercise, therefore, is to find an alignment complying with the above and making where possible encumbrances met to an absolute minimum, especially those requiring major underpinning or acquisition of existing property.

FUNCTIONAL & DESIGN REQUIREMENTS

UNDERGROUND STATION, CUT AND COVER STRUCTURE AND INTERVENTION SHAFT

Standards and Codes of Practices

In Malaysia, all design work generally complies with the appropriate current Standards and Codes of Practice issued by British Standard Institution (BSI). Generally the requirements spelt out in the Design Criteria in specific contracts take precedence over any relevant Standards. Where there are different criteria for design stated in the Contract Document, Standards, Codes of Practice or relevant statutory regulations, the most onerous normally should apply.

Loadings

In Malaysia, the structures are designed for the most onerous combination of loads using relevant partial safety factors in accordance with the requirements of BS 8110. Intensities of some key loads considered for design are listed below.

Train Derailment Loads

As shown in Figures 1 and 2, within tunnels the danger zone is considered to be bounded by the tunnel walls. **Within the Depot and outside of any tunnels** or stations the danger zone is to be taken as 5250mm from track centre-line. **At stations,** it is bounded on the platform side(s) by the platform structure below platform slab level, and above platform slab level by a zone up to 2500mm from track centre-line; at non-platform locations it is bounded by the nearest continuous wall or 5250mm from track centre-line whichever is less.

Design for Train Impacts

When the face of a load bearing element lies outside or does not define the boundary of the danger zone, no special provisions apply. For designs to BS 5400, γ_{f3} should be applied in accordance with the code requirements.

These impact loads should be considered in combination with permanent loads together with appropriate live loads (where inclusion of live load is more critical).

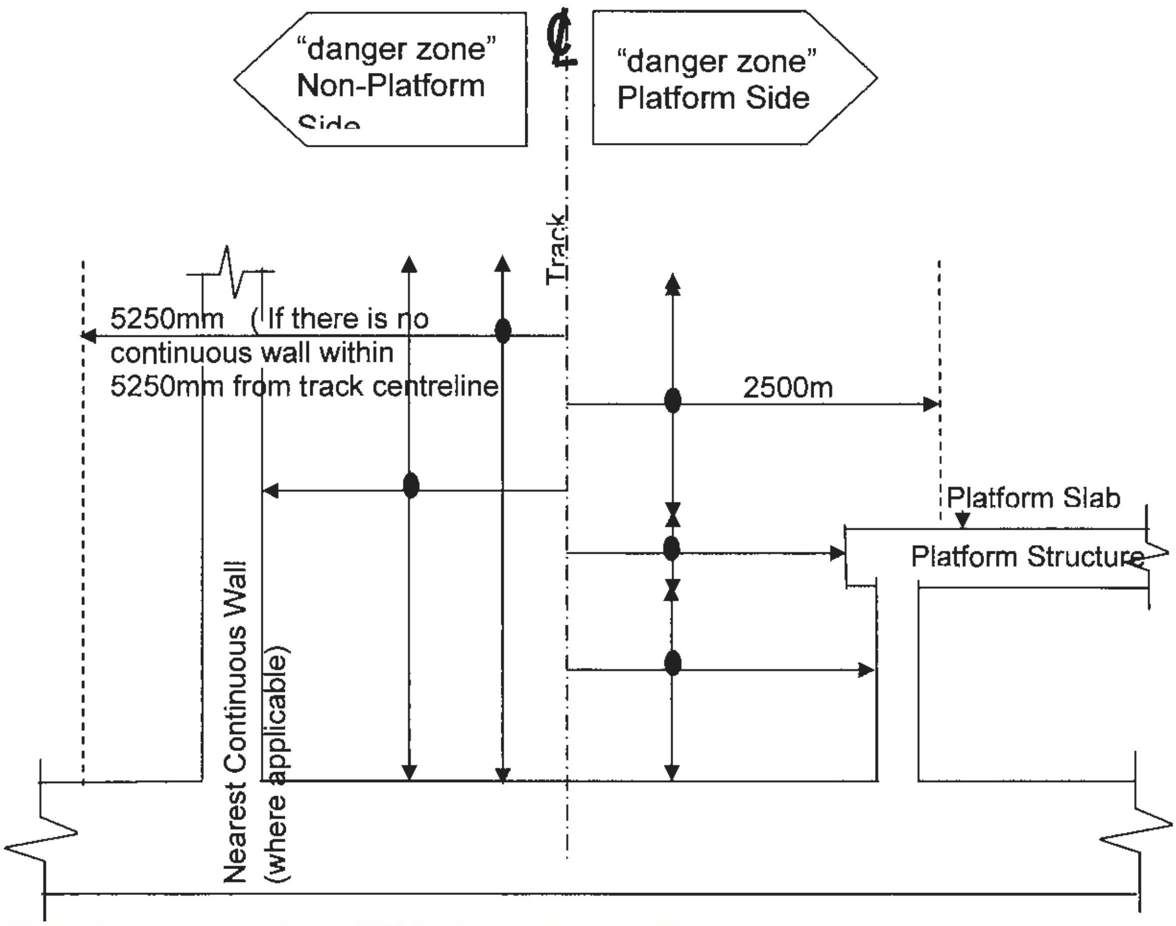


Figure 1 : Zone showing set backs for application of derailment loads

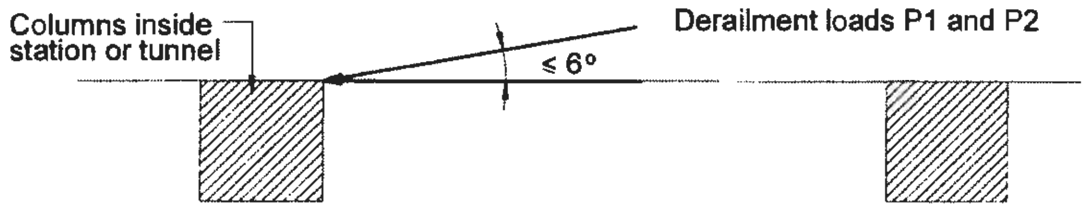
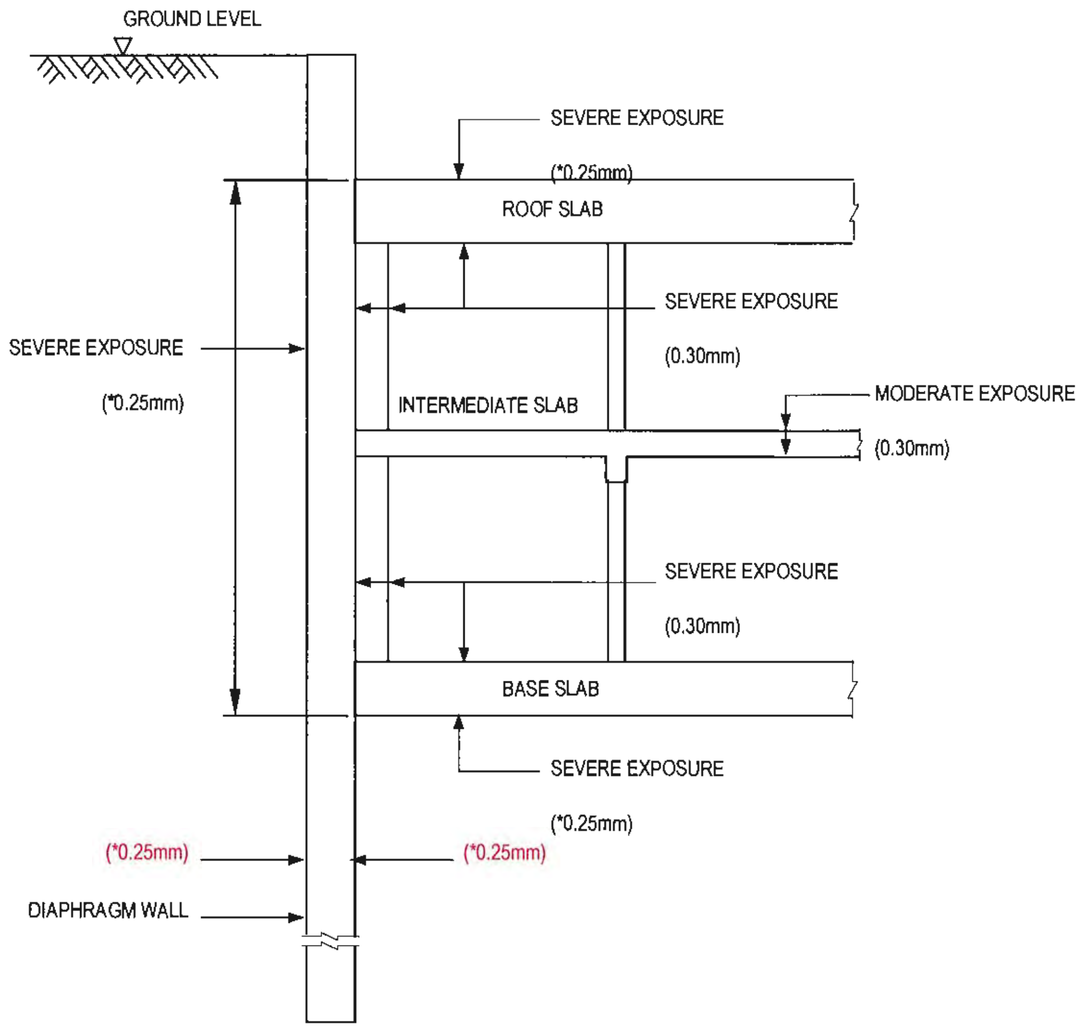


Figure 2 : Shows plan view of direction of derailment loads within tunnel and underground station

Fire Resistance and Durability

All the load bearing structural elements of the underground station and cut & cover structure should be designed to have minimum fire resistance period of 4 hours.

Crack Width& Early Thermal Requirement



For members exposed to earth and/or ground water and forming hull of underground structure, maximum crack width on both external and internal faces due to early age thermal cracking, flexure and / or tension arising from service loads should not exceed the values given below. The crack width should be checked at a plane 40mm from the outermost reinforcement. The widths of cracks from service loads need not be added to those from early-age thermal cracking and shrinkage.

- 0.25mm for external face when subjected to permanent load effects.
- 0.30mm for external face when subjected to transient (temporary) load effects
- 0.30 mm for internal faces.

Waterproofing

A high standard of water-proofing of any underground structure will be required. Groundwater leakage rates should not exceed a general value of 5 ml/m^2/hr. For any 100 square metres of underground station and cut and cover tunnel structure the leakage rate should not exceed 100 ml/hr.

The grade of concrete, treatment of construction joints, areas of slab pours and external membranes should be such that the required standard of waterproofing can be achieved.

Ground Water Seepage

Ground water seepage penetrating the structural walls should be kept to a minimum. As a precautionary measure a cavity wall should be constructed as an inner lining to the structural wall. Within the bottom of the cavity should be formed a drainage channel 100mm diameter laid to falls of not less 1 in 200, and discharging to outlets of not less than 100mm dia. The channels should be lined with a suitable waterproofing membrane. Access panels within the wall should be constructed to permit inspection and maintenance of the drainage system.

At the intermediate levels where floors form an integral part of the structural box, channels should be formed and laid to falls within the slab and connected to outlets of 100mm minimum diameter, situated at 10m centres. Water collected should drain to a sump placed at the lowest level of the station.

Sumps

The station design should incorporate the soil drainage, groundwater seepage sumps to suit the individual requirements of each station.

The size of each sump should take account of the anticipated rate of flow into the sump, the priority rating, the number and types of pumps to be installed and the reserve capacity required above alarm level. This reserve capacity should be determined from consideration of the response time of a maintenance crew to an alarm signal, the accessibility of the sump and the consequential effect of an overflow.

Wherever practicable sumps should be located such as to be readily accessible for inspection and maintenance during times when trains are running. Sumps should be fitted with steel covers and provided with step irons or access ladders within the sump as appropriate.

Provision should be made in the design of the sumps for the discharge mains and power supply cables to the pumps. The layout should be such as to facilitate the removal and replacement of pumps.

Flotation

Underground Structures should be checked for the possibility of flotation at all stages of the construction and throughout the service life of the structure. In the permanent condition, ground water level should be assumed to be at Design Flood Level.

Any loads from developments or from any other structure that would be beneficial to stability against flotation should not be considered in the flotation assessment. Flotation check is not required for drainage culverts with weep holes.

The self-weight of the structure should be divided by a partial safety factor of 1.10. For railways, first-stage concrete (if any) may be considered as self-weight of the structure. Weight of partition walls, floor finishes, road surfacing, false ceiling, equipment and other superimposed dead load, etc. should not be considered.

The weight of backfill material over the structure should be divided by a partial safety factor of 1.1. Since the design water table is above the finished ground level, the effective weight of the backfill should be based on the submerged density of the material. In the calculations backfill within the top 1.5 metres of the ground surface should be ignored.

The overall factor of safety against flotation should be not less than 1.1, except when soil friction is omitted the overall factor safety against flotation should be not less than 1.0.

In evaluating the design frictional resistance to uplift between elements of the structure and the surrounding ground or backfill, a partial safety factor of 2.0 on the design shear strength should be used. For cohesive soils, an adhesion factor should be determined from suitable published data (e.g. Tomlinson), and for cohesionless soils earth pressure coefficients taking into account the effects of the following as appropriate:

1. The shear strength of the backfill;
2. The method of placing of backfill material;

3. The temporary support system, either left in place or extracted;
4. Grouting;
5. The use of bentonite;
6. The depth below ground surface and
7. The waterproofing system for the structure.

With respect to item 7 above, where critical shear interface is along the waterproofing membrane, no frictional resistance should be used. No shear resistance should be allowed within 2 metres of the ground surface.

Measures to Counteract Flotation

Suitable measures to counteract flotation forces should be incorporated in the design. The measure(s) chosen should suit the particular conditions and method of construction and may include:

(i) Toeing in of the base slab into the surrounding ground or fill.

(ii) Increasing the dead weight of the structure by:

- Thickening of structural members.
- Providing an extra thickness of concrete beneath the base slab tied into the structural base slab.
- Deepening diaphragm walls.

(iii) The provision of tension piles.

Where the base slab is toed into the surrounding ground or fill, the shear resistance may be obtained from the shear resistance of the ground or fill as appropriate. The shear resistance of the ground or fill above the toe should be divided by a partial safety factor 2.0 and the adhesion factor should not apply. The value of the weight of ground above the toe should be calculated as for the backfill material, unless mass concrete is used. Where toes are provided, the minimum toe projection should be 0.5m.

The value of the weight of any additional thickness of concrete should take into account the increased volume of water displaced.

Stability of Excavation

Base Heave in Soft Clays

The stability of the completed structure against failure due to base heave under the structure should be checked. Base heave should be checked using moment equilibrium method and required factor of safety (FOS) is 1.2 if moderate conservative values of undrained shear strength is used and where the vertical shear resistance along retained ground shallower than the excavation is ignored (Kohsaka& Ishizuka, 1995).

Hydraulic Failure

For excavation at sites with groundwater on the retained site above the base of excavation or where artesian pressure is present, a hydraulic failure check needs to be carried out. If the toe of the wall does not penetrate into an impermeable layer or to a sufficient depth, base instability caused by piping will occur if the vertical seepage exit gradient at the base of the excavation is equal to or more than unity.

For Sandy or Cohesionless soil the potential for hydraulic failure of an excavation can be estimated using Terzaghi'smethod. The factor of safety (FOS) for Terzaghi's method should be 1.2 for temporary works and 1.5 for permanent works or long term temporary works. Notwithstanding the above, seepage analysis should be carried out to ensure there will be no adverse effect on the existing ground water level in the surrounding ground (e.g. should not cause lowering of more than 1m groundwater level in the surrounding ground).

Toe in Depth

Toe-in stability check should be carried out to determine the toe-in depth or embedment of the retaining walls to ensure that adequate passive resistance can be mobilised. The minimum factor of safety as defined by Equation (1) should be 1.0

Stray Current

The Stray Current Corrosion Control (SCCC) system shall generally include the following:

Isolation and/or control of all possible stray current leakage paths to minimise stray current effect on the railway facilities, adjacent structures and public utilities.

Detection and monitoring of stray currents which do occur.

Stray current drainage (collection) system which, when put into use, provides a return path for the stray current back to the traction substation negative busbar via drainage diodes.

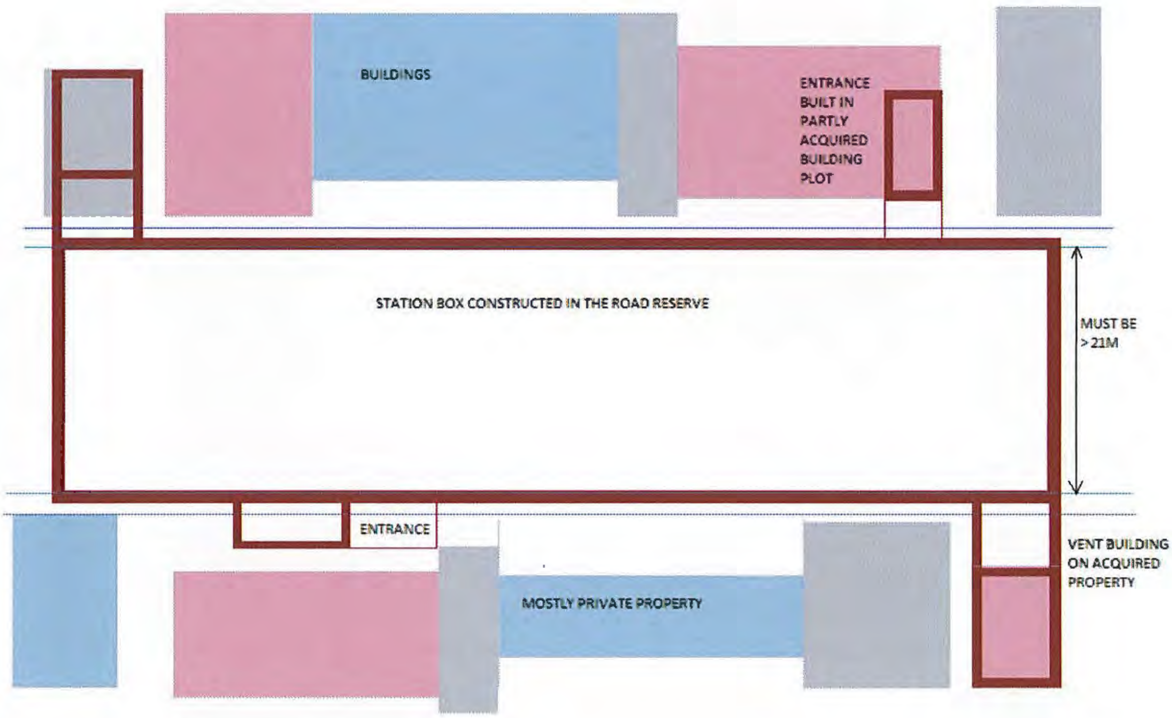
The amount of stray current that will leak out from the track and power system shall be assessed by the Electrical Services contractor. Based on this amount of leakage current, the Civil Contractor shall prepare a quantitative analysis of the corrosion effects on the railway structure and appropriate provisions made in the design to ensure the 120-year design life for railway structures is achieved.

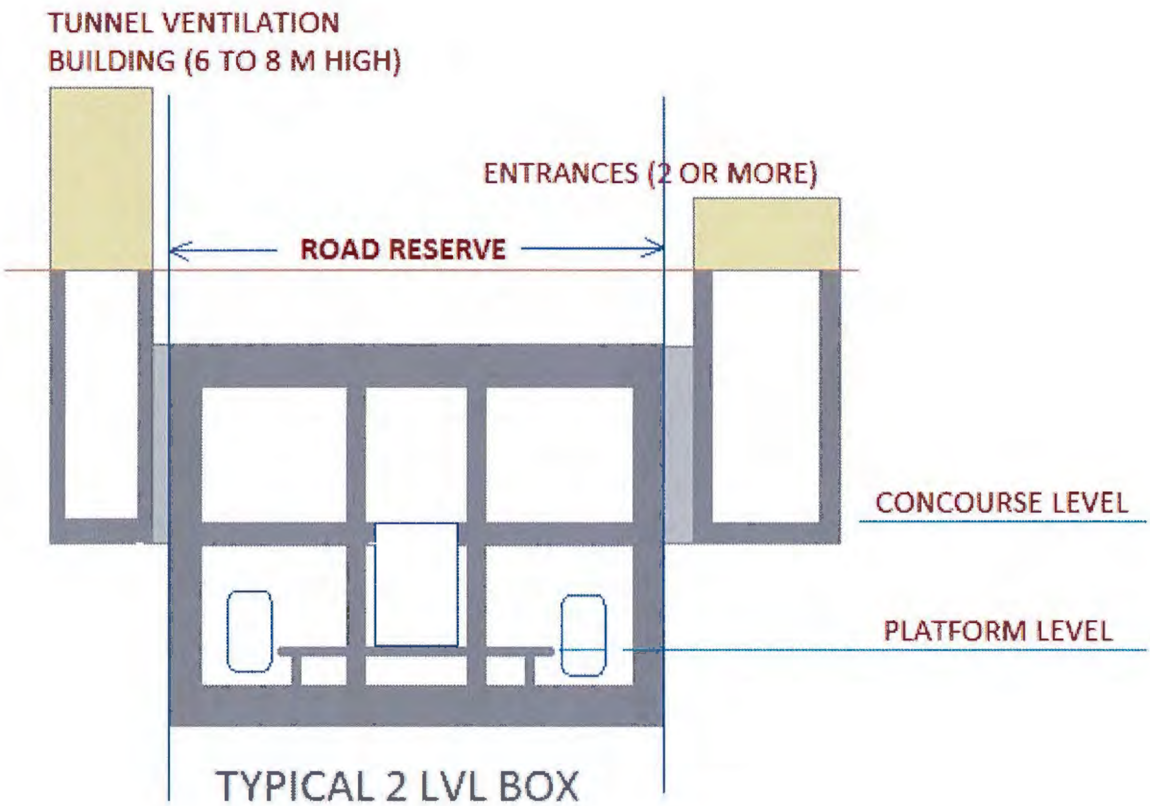
FIRE SAFETY

All underground stations or structures with public or staff access require **to be designed for safe evacuation in case of fire or other emergency.**

The requirements of such safety are contained in NFPA 130, the standard for fixed guideway transit and passenger rail systems (current edition 2010).

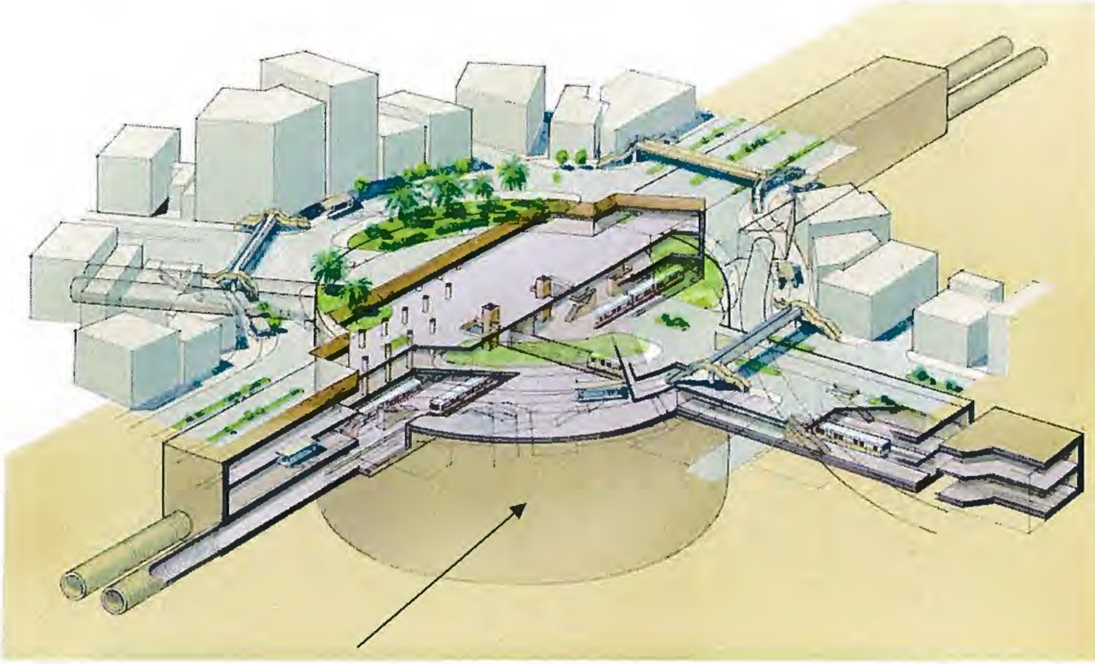
CONSTRUCTION AND QUALITY REQUIREMENTS (TYPICAL)





CASE HISTORIES

The MRT department of Kaohsiung City Government (KMRT) is implementing this project through a BOT contract. With an approximately combined length of 42.7 km, the Red and Orange lines of the system will have 37 stations and 3 depots. The North-South Red line is approximately 28.3 km with 23 stations of which 15 are underground. The East-West Orange line is approximately 14.4 km with 14 stations of which 13 are underground. Of the three depots, two are located on the Red line, one at each end and the third, the main depot, at the east end of the Orange line.



Cofferdam for Kaohsiung MRT Interchange Station

The largest ever attempted cofferdam in an urban environment has been constructed in Kaohsiung. It is 140m diameter with 3m wide x 1.8m thick wall panels, constructed to 60m depth with a vertical accuracy of 1 in 1000 using hydrofraise reverse circulation rigs. The cofferdam is part of the temporary works for the 2-level Interchange station and the transfer track between Red & Orange Line in Kaohsiung at the site of a busy interchange. The station has split base slab, at 20m and 27m below ground level and the entire cofferdam is decked over during construction to allow interrupted traffic flow at a junction of the two busiest roads in the city.

The proposal for a cofferdam was put forward by the design build contractor. The excavation will contain the stations and transfer track and be unbraced allowing relatively free access for construction. The stability of the cofferdam relies totally on generating hoop load from external soil and water pressures with very little reliance on cantilever action.

D&B contractor had constructed a similar sized cofferdam in Japan but not in the same ground conditions and not in an urban environment.

As part of designer's role as Safety and Quality Consultant a comprehensive risk assessment was called for to cover aspects of design, construction, dewatering and excavation. The assessment included connections with adjoining cut-and-cover structures and tunnels and the sequence of their excavation. designer's experts worked with the contractor to develop the risk assessment and the mitigation actions to reduce all risks to as low as reasonably practical.

Following this exercise, designer insisted on the water level inside the cofferdam to be lowered to –20m before start of excavation to demonstrate the generation of hoop load. Rate of water extraction from the cofferdam resulted in a behaviour that was not predicted and de-watering design had to be reviewed.

During excavation of the cofferdam designer's resident staff undertook a close review of the monitoring data and at critical stages in the dewatering and excavation process called on the contractor to justify the actions being taken against the risk assessment that resulted in a change to the design of the dewatering system. The change brought about increased confidence in the stability of the works and allowed an increase in the rate of excavation thereby allowing better progress of the works. An overall saving of 6 months in the construction allowed the client to meet his line completion date.

The Site

Reverse Circulation Rig