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8390 Hong Kong Mass Transit Railway Modified Initial System: design and construction of underground stations and cut-and-cover tunnels

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The Paper sets out the basis on which the design and construct contracts for the underground civil engineering works for the railway were let, and refers to the assumptions on construction methods adopted by the consultants when carrying out the planning and outline design of the stations. The Paper explains the extent to which contractors varied those assumptions and adopted different construction techniques to suit their own preferred methods, and their interpretation of the restraints. The design and construction of two of the stations, where the contractors selected radically different methods of construction, is described in detail.

Introduction

For the reasons given in Paper 8389, the contracts for underground stations and cut-and-cover tunnels were let on the basis of the contractor carrying out the detail design to suit his chosen method of construction.

2. The contract packages were in some cases for individual stations, in some cases for stations with adjacent tunnels, and in other cases for two or three stations. Running tunnels, both bored and cut-and-cover, were dealt with in a similar manner. The selection of contract packages was based on a number of factors, including whether a structure could be handled by a local contractor and, if not, if the size of the contract was sufficient to attract strong overseas competition, and the availability of work sites.

3. Where practical, contractors were encouraged to bid for a mix of station and tunnel contracts not only to obtain discounts for more than one contract but also to rationalize the use of available work sites and facilitate access and excavation.

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4. Where practicable, work such as the diversion of utility services away from the station areas was carried out prior to the letting of contracts. Certain structures, such as ventilation shafts which interfaced with private developments, were let as advanced contracts, or incorporated in private building contracts.

Table 1. Underground stations—adopted construction methods

Station	Depth of excavation, m	Cover to roof slab, m	Depth to rock from surface, m	Engineer's assumed method	Temporary works
Choi Hung	20	0–3	*	Temporary Berlin wall with preboring or diaphragm walls	Permanent walls
Diamond Hill	22	3	†	Steel I section king piles and intermediate sheet piles	Permanent walls
Wong Tai Sin	24 max.	3·5–6·5	*	Diaphragm walls	Permanent walls
Lok Fu	27	2	0–30	Bored tunnel	Berlin wall of steel piles and concrete lagging—ground anchors
Kowloon Tong	18	2	†	Diaphragm walls	Part permanent walls—part Berlin type—ground anchors
Shek Kip Mei	18–24	1·5–6·5	0–30	Open cut in rock, sheet piling with ground anchors in soil	Berlin wall, part strutted, part ground anchors
Prince Edward	28	2	16–30	Diaphragm walls	Permanent walls
Argyle	25	3·5	†	Diaphragm walls	Permanent walls

* Not known.
† Not known; large boulders.

Information issued to tenderers, and Engineer's assumptions

5. The contract documents required the contractor, with certain exceptions, to carry out the design and construction of the permanent and temporary works. To enable him to carry out his commitments with maximum flexibility this information

Proximity to buildings	Walls	Construction sequence	Special measures
One end only	Hand-dug interlocking caissons	Top down	Skeletal roof of cross-beams with precast T beam infills
No	Hand-dug caissons for steel piles and concrete jack arches	Top down	Walls are to be removable for future widening
Medium height housing blocks	Diaphragm walls	Top down	Roof was clear spanning during excavation with concourse suspended from it
High rise housing block	In situ	Bottom up	Dewatering by ground treatment and wells
No	Part diaphragm walls, part in situ	Bottom up	—
High rise housing blocks and schools	In situ	Bottom up	Short length of station platforms in bored rock tunnel
High rise commercial and residential	Benoto type secant piles and hand-dug caissons	Top down	Extensive grouting was used, plus dewatering and limited recharging
High rise commercial and residential	Benoto type secant piles	Top down	Columns extended to underlying rock and vertically anchored; some areas of slab also anchored; grouting to walls; use of recharge wells

contd over

was presented in both mandatory and non-mandatory (for information) categories.

6. In the mandatory category were

general conditions of contract
general specification
design specification
materials and workmanship specification
particular specification
general layout drawings
architectural arrangement drawings
line location drawings
drawings of affected utilities

7. The non-mandatory advisory information, which was provided or made available to view, included

geotechnical information
building plans of structures adjacent to site
Engineer's assumptions

Table 1 (contd). Underground stations—adopted construction methods

Station	Depth of excavation, m	Cover to roof slab, m	Depth to rock from surface, m	Engineer's assumed method	Temporary works
Waterloo	28	2	0–27	Part open cut, part diaphragm walls	Permanent walls
Jordan	18–23	0–4·5	4–20	Diaphragm walls and rock anchors, in situ underpinning	PIP pile walls and 7 levels of steel strutting
Tsim Sha Tsui	17–21	3·5–7·5	9·5–13·5	Diaphragm walls and rock anchors, in situ underpinning	PIP pile walls and steel strutting
Admiralty	25	0–3	20	Diaphragm walls to rock; rock anchors and in situ underpinning	Combination of open cut, anchored sheet piling and permanent walls, also slurry trenches
Chater/ Pedder	28	3	35‡	Diaphragm walls	Permanent walls with struts

‡ But rock level not proven in some sections.

8. The contract nominated British Standards or their equivalent as the basis for design and in particular BS 153 and BS 449 for steelwork and CP 110 for concrete structures. Other national or international codes could be used if approved by the Engineer. Most contractors decided to adhere to British Standards, which made the approval of designs that much easier.

9. The design specification defined such items as

(*a*) loading combinations to be used;
(*b*) minimum horizontal and vertical loads from buildings adjacent to site;
(*c*) minimum permitted water drawdown levels;
(*d*) seismic loading;
(*e*) anti-flotation criteria;
(*f*) minimum superimposed loads on floors.

10. The general layout drawings illustrated the required configuration and proportions of the station, entrances, vent shafts and adjacent tunnels, which had been developed by the Engineer from his original design work, or were necessary to meet operational and plant space requirements. These drawings also showed the

Proximity to buildings	Walls	Construction sequence	Special measures
High rise commercial and residential	Benoto type secant piles to rock, then in situ	Top down	Underpinning to walls
High rise commercial and residential	In situ	Bottom up	Half of station anchored to underlying rock
High rise commercial and residential	In situ	Bottom up	Part of station anchored to underlying rock
No	Part diaphragm walls, part in situ	Bottom up	Part of station anchored vertically to underlying rock; underpinning to diaphragm walls
High rise commercial and hotels, low rise historic buildings	Diaphragm walls	Top down	Special measures to construct walls and groundwater recharging

disposition of plant and services within the station. The contractor was required to design the structure to given superimposed loads and ultimately to recheck his design when precise loading became known. Only those dimensions and levels which had to be adhered to were given on the drawings.

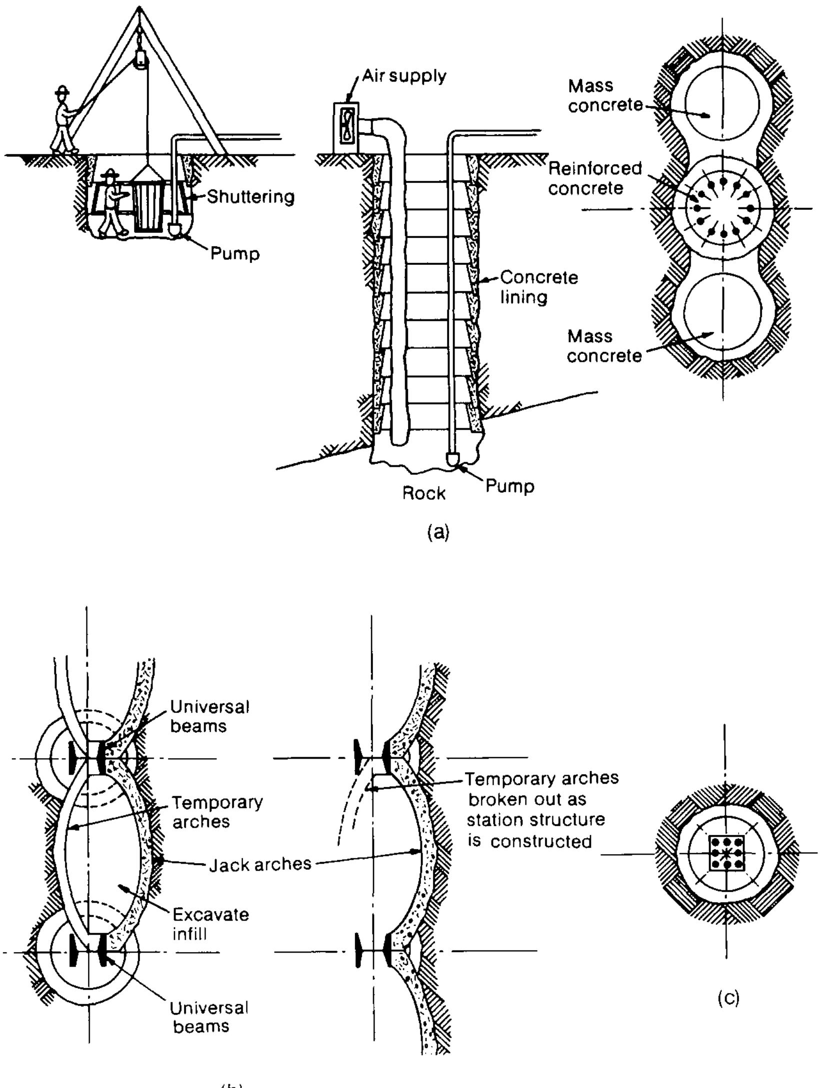


Fig. 1. Hand-dug caissons: (a) wall construction, type 1; (b) wall construction, type 2; (c) construction for isolated reinforced concrete or structural steel columns

11. The contract also required the successful contractor to develop and detail all fittings and finishes within the stations. The architectural arrangement drawings and the specification formed the basis for this work.

12. The line location drawings gave the precise position of the running lines together with the relative positions of the stations and tunnels.

13. The services to and from the station were to the Engineer's design and in general the contractor provided only those elements which were within his works area or could affect his programme.

14. The Engineer's assumptions described the method of construction visualized by the Engineer and the assumptions from which these schemes were derived.

15. A set of geotechnical drawings and data showed the position, depth and strata of several boreholes taken at and adjacent to each construction site. Cores from the boreholes were also available for inspection. The contractor was obliged by the contract to amplify and reconfirm this data after the award of contract.

Construction methods

16. There were twelve underground stations incorporated in the 25 major civil engineering contracts let.

17. In general the Engineer proposed that these should be constructed top down using diaphragm walling. However, bored tunnel construction for Lok Fu station, top down construction within sheet pile walls at Diamond Hill station and bottom up construction in open cut in rock at Shek Kip Mei were envisaged. Table 1 indicates the extent to which contractors modified the Engineer's assumed methods.

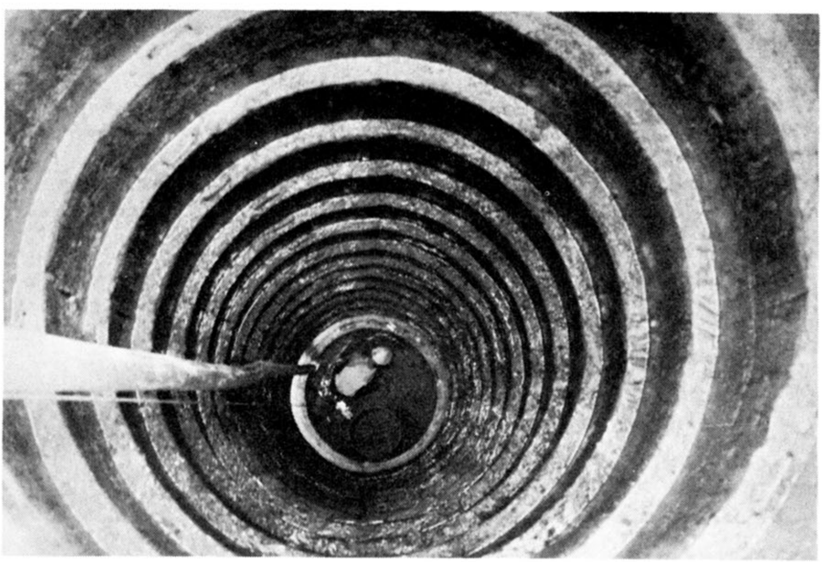


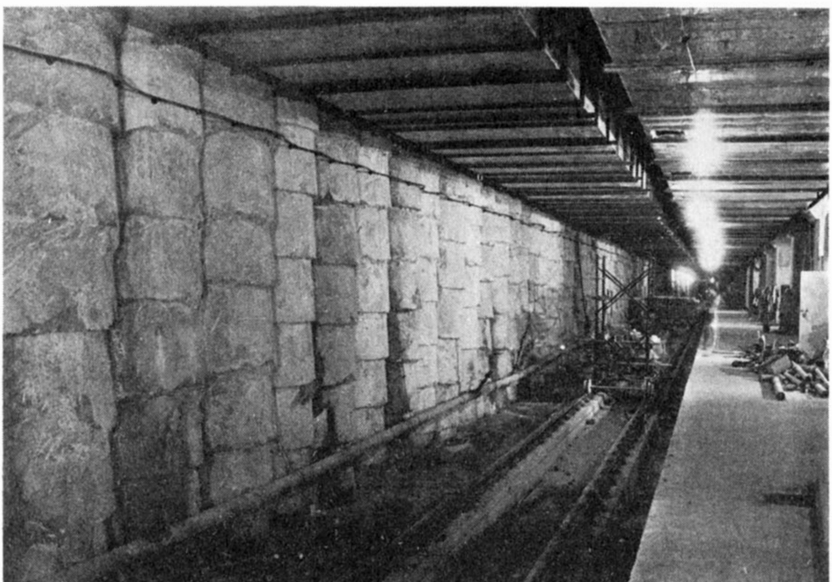
Fig. 2. Hand-dug caisson for king pile

18. Some of the contractors adopted the Engineer's sequence of working but utilized a different method of wall construction, while others adopted a construction method with which they were more familiar.

19. A local engineering technique was adopted to form the station walls at Choi Hung and Diamond Hill stations (Figs 1 and 2). For Choi Hung the contractor used the hand-dug caisson (HDC) technique to form walls of interlocking piles which were reinforced to resist the bending moments and shears from the completed structure (Fig. 3(a)). This system was modified for the semi-permanent walls at Diamond Hill by the introduction of arched plates spanning between the king piles installed in the caissons (Fig. 3(b)). The columns in both stations were installed before excavation commenced using the same caisson technique. To facilitate excavation, the roof of Choi Hung station was constructed using a system of spaced, in situ beams. The gaps between these beams were infilled with precast beams. A solid roof slab with temporary access holes was used at Diamond Hill.

20. The stations, except for Jordan and Tsim Sha Tsui which were constructed in the heavily built-up areas with tall buildings abutting the site, were constructed using preformed walls and top down construction. The contractor for Jordan and Tsim Sha Tsui used bottom up construction within a strutted cofferdam which was formed using a proprietary walling system.

21. One particularly difficult location was the site for Chater station in the heart of the business centre of Hong Kong. The sides of the station, which in part was four levels deep, ran very close and parallel to existing high rise buildings and two low

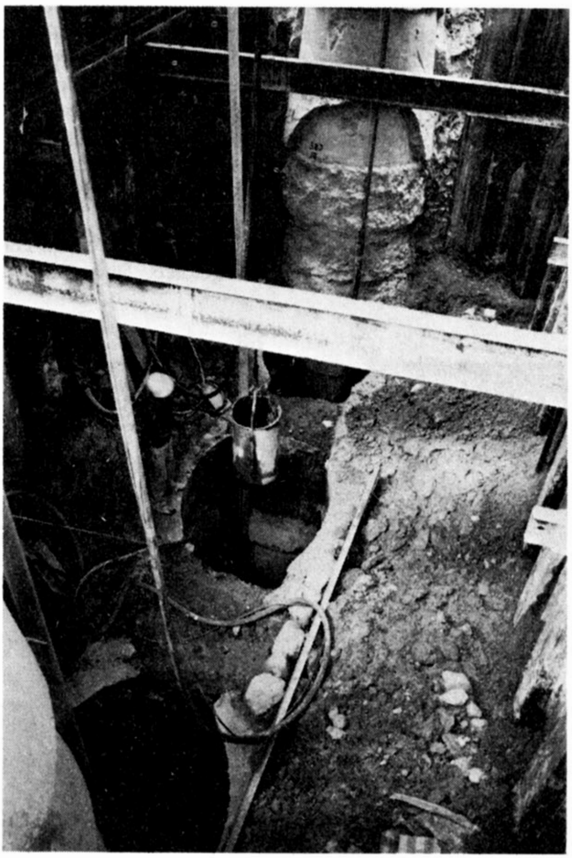


(a)

Fig. 3. Hand-dug caissons, wall construction: (a) Choi Hung; (b) Diamond Hill

rise structures which were of historical interest to Hong Kong. These latter buildings presented engineering difficulties as little information was available on the foundations. The contractor tackled the construction using diaphragm walls and excavating the station from the top down. Special measures such as raised guide walls and high density bentonite were employed in the construction of some of the diaphragm walls. After construction of the walls a system of groundwater recharging was adopted in the vicinity of one of the old buildings to limit further settlement. The station was required, at its western end, to carry a high rise building which was partially constructed simultaneously with the below-ground works. The construction method adopted by the contractor was to support the building on barrettes. On completion of the excavation it was necessary to transfer the initial loads in the barrettes to a system of hand-dug caisson piles founded in rock.

22. Although permanent diaphragm walls were used for the perimeter of Wong



(b)

Tai Sin station an unusual overall top down scheme was adopted by this contractor. The roof slab, which was constructed in two halves to maintain traffic flow, was designed to span initially the full width of the station. Excavation proceeded to concourse level where the slab was temporarily suspended from the roof so that excavation could progress to track slab which was then concreted. Finally, the internal columns were constructed to their full height and concreted into the completed structure when the hangers were released.

23. One of the most critical civil engineering contracts on the project was for the construction of Argyle and Waterloo stations and Prince Edward substation under Nathan Road, the main road artery of the Kowloon peninsula. Prince Edward was built initially as a half station and will be extended to its full size during the construction of the first railway extension. These stations are deeper than normal since they incorporate two track levels. The ground conditions varied from soft at Prince Edward to predominantly rock at Waterloo and this necessitated the underpinning of the permanent walls of this station which terminated in the high level rock. All three stations were constructed using the Benoto piling technique to form a permanent secant pile wall (Fig. 4). Some portions of wall were constructed with hand-dug caissons; this technique was used more extensively than originally planned in order to ensure that critical dates were met. Extensive curtain grouting to limit drawdown was resorted to and this proved very effective.

24. Whenever the opportunity arose to use the bottom up method of construction, this was adopted even if it involved considerable ground stabilization and extensive use of rock and soil anchors. This technique was adopted for Lok Fu, Shek Kip Mei and Admiralty stations.

25. The station at Lok Fu was constructed partly in bored tunnels and partly in an open cut excavation with a bottom up sequence. Temporary retaining walls

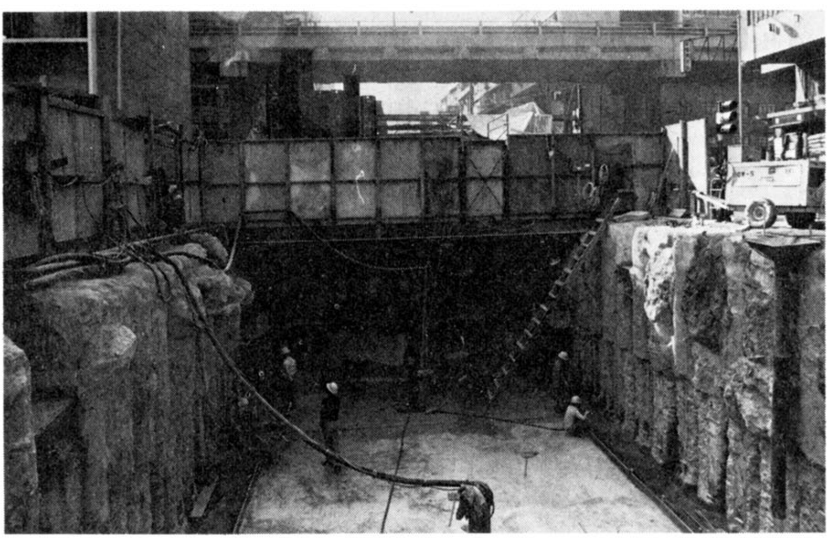


Fig. 4. Benoto pile wall

based on the Berlin construction method were installed by pre-augering holes, into which were placed steel double U section piles. As excavation proceeded ground anchors were installed between the U sections, and concrete panels were cast between the piles. The excavation reached a maximum depth of approximately 24 m and was extended at one end to provide an access shaft for the bored tunnels.

26. Admiralty, a large three-level interchange station shaped in plan like a truncated triangle, was constructed on a roughly oblong work site. The contractor elected to vary the temporary and permanent works designs as the site conditions varied. This station included a substantial portion of in situ structure constructed within an open cut section. The upper level of the excavation was either battered back or retained by anchored sheet piling. The lowest portion was cut vertically into the rock and the rock was secured where necessary by anchoring. The track slab of the wider section of the station was vertically anchored to the underlying rock with a pattern of rock anchors as a permanent anti-flotation measure. The portion which included the running tunnels to the east, however, was constructed top down using diaphragm walls terminating in rock. These were subsequently underpinned and extended down to the lower track slab level.

27. For Kowloon Tong station, as with Admiralty station, a mix of construction methods was employed. The main body of the station was constructed using diaphragm wall techniques while the end portions were constructed within temporary walls of king piles and in situ concrete panels. Both the temporary and permanent walls were supported by ground anchors during excavation. The construction mix necessitated a bottom up sequence of construction.

Cut-and-cover tunnels

28. In general the cut-and-cover tunnels were constructed within strutted sheet-piled cofferdams. Only one section, close to rather sensitive buildings, was constructed within a braced cofferdam, using a proprietary packed-in-place (PIP) pile system.

Implications of construction methods on design

29. The overall construction programme was very short. Furthermore the nature of the project with its interrelationship of contracts led to the adoption of liquidated damages against a number of key dates in each contract. It was therefore particularly important for a contractor to hold his programme and to ensure that the construction process had sufficient flexibility so that if work was held up in one area of the site, its effect on the overall programme was minimized. His method had to perform better than the minimum required to permit changed site conditions to be quickly overcome.

30. Even a typical two-level station was a difficult contract to complete in the timescale required with limited working space and usually in a heavily built-up area.

31. The body of such a station was 250 m long, 25 m wide and 13 m deep. With 3 m cover, basic quantities were

excavation	100 000 m^3
concrete	25 000 m^3

32. This amount of work was reflected in the drawings. Approximately 650 working drawings for the civil works and 300 for the architectural finishes were required for a single station contract.

33. Those contractors who elected to use preformed permanent walls as temporary works were required to complete the design of the station structure at a very early stage. The various intermediate loading cases also required early calculation to determine the necessary reinforcement.

Table 2. Argyle station job statistics

Contract period		200 weeks
Peak labour, including subcontractors		350 men
Station box dimensions and levels above principal datum:		
length		270 m
width (inside walls)		22 m
depth (ground level to underside lower track slab)		24·5 m
perimeter		680 m
ground level		+4·0 m to +5·0 m
top of roof slab level (and slab thickness)		+1·0 m (1·3 m)
top of concourse slab level (and slab thickness)		−4·7 m (0·6 m)
top of upper track slab level (and slab thickness)		−11·0 m (1·1 m)
top of lower track slab level (and slab thickness)		−17·8 m (2·1 m)
Number of entrances		13
Number of vent shafts		3
Wall piles—total length		17 700 m
Excavation:		
wall piles and caissons	56 000 m^3	
main box	163 000 m^3	
entrances/vents	22 000 m^3	
total		241 000 m^3
Concrete:		
wall piles and caissons	56 000 m^3	
station slabs	39 000 m^3	
entrances	7 000 m^3	
roads etc.	6 000 m^3	
total		108 000 m^3
Permanent steel:		
rebar	4000 t	
wall beams	4700 t	
box columns	600 t	
shear plates and shoes	200 t	
total		9500 t
Temporary steel:		
traffic deck	500 t	
station struts	1000 t	
entrance sheet piles and struts	500 t	
total		2000 t

34. The design of the connections joining the roof and floor slabs to preformed walls is complicated. The connections are expensive, intolerant to error, and difficult to waterproof. Careful thought was required to assess these effects, particularly the achievable fixity of the connections and its corresponding influence on the bending moments in the frame.

35. A further disadvantage of the use of permanent walls as temporary works is the difficulty of waterproofing the completed structure. Careful thought given to the details at an early stage and continuous attention during the construction period were required to produce a dry station.

36. The deep cut-off to slurry and piled permanent walls, coupled with their extension to the surface of the ground, exacerbates a possible damming effect of these large underground structures on the moving groundwater in parts of Hong Kong.

37. The known advantages of using permanent walls temporarily during the critical stages of excavation must be tempered by the high early demands on design resources that this system makes and the corresponding effect on the programme.

38. Sequence of construction also plays its part in affecting the basic design. The more obvious example is the installation of the permanent columns out of sequence with the casting of the floor slabs. Some contractors were prepared to accept the complication of ultimately jacking loads into columns and designing the reinforcement in the floors to suit the varying loading conditions, thereby facilitating bulk excavation and the completion of the lower slab to gain a transient programme advantage.

39. The constraints placed on the contractor by the specification and known site conditions undoubtedly limited the selection of a particular construction method. In the event it is of interest to note the tailoring to the actual site conditions and the adaptations of existing and tried techniques which this type of contract encouraged.

Detail design of Argyle station

40. The GKL Joint Venture, comprising Gammon (Hong Kong) Ltd, Kier International Ltd, the Sponsors, and Lilley Construction Ltd, were awarded the contracts for the detail design and construction of Waterloo, Argyle and Prince Edward stations together with the running tunnels between.

41. Argyle station is the largest of these structures and the main station box structure contains a concourse level, two trackbed levels, 13 entrances and three vent shafts. The job statistics are set out in Table 2.

42. Figure 5 shows a plan and section through Argyle station—constructed below the main street of one of the most densely populated areas in the world. The close proximity of commercial and residential tower blocks, some founded on piles terminating close to the lowest excavation level, favoured a top down method of construction and the choice of wall system.

43. The need to minimize building settlement, the desire to use established methods with plant occupying minimum space, operating under balconies in close proximity to pedestrians and traffic, and the need to cope with boulders and bedrock were the main considerations. Secant bored piling, with 914 mm × 305 mm universal beam structural members in every pile was the chosen system for the permanent walls to meet these criteria.

44. Active and at rest earth pressures for the construction and permanent cases

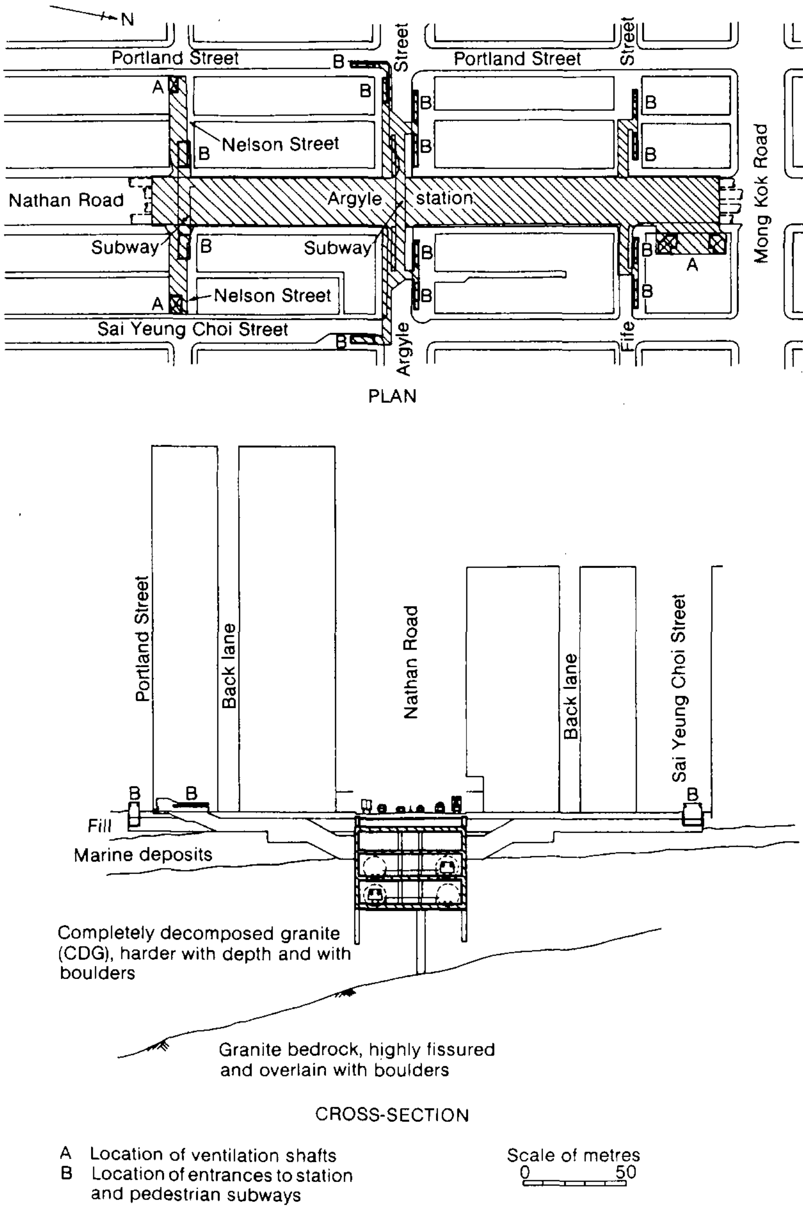


Fig. 5. Argyle station

were used with plastic design method with limit state checks. Surcharges of 50–335 kN/m^2, applied at levels to suit the actual building foundations, were accommodated by varying the universal beam weight and size where rock level permitted.

45. The structural analysis of the slab and column interaction used a plane frame program, although checks were made using finite elements. However, escalator slots and plant room areas presented significant complications. Station columns, with design loads up to 15 000 kN, comprised 1000 mm × 800 mm grade

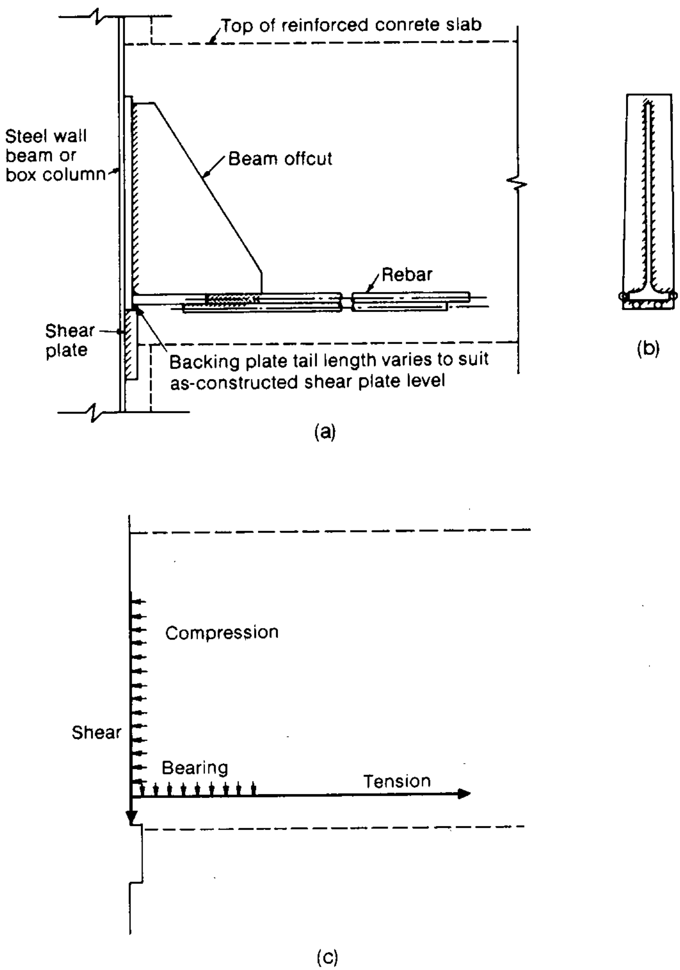


Fig. 6. Argyle station—detail of shear shoe and plate: (a) side view; (b) end view; (c) force transfer

50B steel boxes 20 m long. A concrete core provided additional stiffness only. The load transfer from slabs to walls and columns was by a shear shoe and plate arrangement (Figs 6 and 7). The effect of buoyancy and the stress redistribution in the transition from the construction to the permanent state were taken into consideration.

46. A major redesign of Argyle station was carried out to accelerate construction by the temporary omission of one line of columns. This involved hanging the concourse slab, temporarily propping openings and preloading columns when finally installed. It illustrates the flexibility that can be achieved in a major project by the design and construct approach.

47. The design was started in Kier's UK office and continued at site by 18 expatriate and local engineers. About 1300 drawings were produced and checked by the consultants.

48. Major temporary works, also designed on site, included a traffic deck over the station to accommodate three lanes of public traffic, contractors' plant and public utility services. The geotechnical aspects included dewatering, grouting and settlement.

Construction of Argyle station

49. Work commenced on the Argyle station site in March 1976 and the completed station was opened to the public in December 1979.

50. Figures 8 and 9 indicate the congested nature of the site. The contract required that vehicular and pedestrian flow along Nathan Road and side streets be maintained throughout the construction period and, from the first stages of utility

Fig. 7. Argyle station—shear shoe and plate

diversion and wall construction, the requirements of the police, highway authority, public transport companies and other interested parties were incorporated in the planning. Surface activities such as wall and column construction, ground treatment and utility diversions were restricted to one side of Nathan Road at a time, and on completion of the walls, and prior to bulk excavation, vehicular traffic was diverted onto a three-lane traffic deck the full length of the station.

51. The permanent in situ station walls were formed of 1·2 m dia. secant piles at

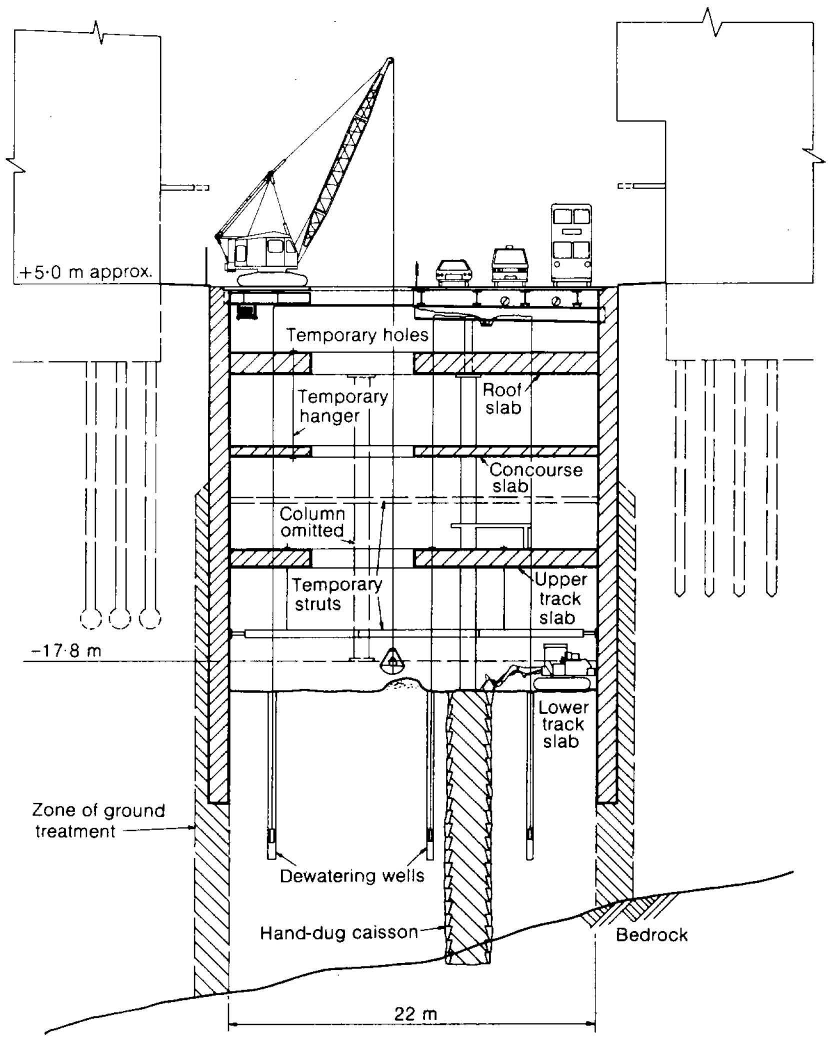


Fig. 8. Argyle station—typical section during excavation for lower track slab

Fig. 9. Argyle station site congestion

Fig. 10. Benoto piles in permanent wall

1·0 m centres by Benoto piling rigs (Fig. 10). Up to five rigs were used simultaneously at Argyle, each attended by a 30 t capacity crane which inserted the 30 m long universal beam on completion of the bore. The proximity of the wall line to the overhanging adjacent buildings necessitated the temporary demolition of canopies and removal of projecting air-conditioners, to allow working space for piling rig and crane operation. Concrete for the piles was placed by tremie pipe; PFA and retarders were incorporated in the mix to reduce early strength to facilitate the cutting of the interlock between adjacent piles.

52. Where pre-war buildings along Nathan Road had balconies projecting over the wall line as low as 3·5 m above footpath level, hand-excavated caissons were constructed in sequence within local grout curtains and, when filled with concrete and universal beams, formed the permanent wall.

53. To minimize settlement of adjacent buildings from the dewatering effect of later excavation stages, a bentonite cement and silicate grout curtain was formed below the wall toe to seal off the station box from the surrounding high water table where an adequate cut-off could not be achieved by the Benoto rigs. This grout curtain proved extremely effective and restricted the abstraction rate to less than 0·0045 m^3/s from within the total station box under a differential water head across the walls of over 20 m.

54. The station columns were inserted from the surface on to prepared foundations to rock within hand-dug caissons. Some difficulty was experienced in the lower levels of caisson excavation, the deepest being taken to sound rock at 42 m below ground level. The steel box columns, up to 19 t weight and 20 m long, were transported to the site and lowered into the caissons at night.

55. Excavation commenced from the ends of the station on completion of the walls and traffic deck and installation of a system of internal deep wells whose function was to dewater the inside of the box to below lower track slab formation level. This improved the passive resistance of the soil and facilitated handling of the excavated material.

56. Working headroom under the temporary struts, the range of soils from soft marine clays to hard decomposed granite, availability of equipment, and the required rate of progress were significant factors in the choice of excavation method (Fig. 8).

57. Yutani SL 1400 low ground pressure tracked face shovels excavated beneath completed concrete slabs and loaded into muck skips or stockpiled for grabbing. The material was raised to traffic deck level by crawler crane through temporary mucking-out holes and hauled 15 miles to tip by lorries. Small dozers and crawler loaders cleared and levelled the formation prior to the laying of the smooth blinding concrete which formed the soffit shutter of the next structural slab.

58. Up to four faces were worked simultaneously for two shifts, seven days a week, and over 160 000 m^3 of material were excavated in 40 weeks with a peak weekly output of 9000 m^3.

59. The slabs were concreted in bays of up to 1000 m^3, the concrete being delivered at road level by mixer trucks and discharged down flexible trunking to the required locations. Slab construction proceeded simultaneously with, and hard behind, the excavation faces.

60. The 13 entrances were constructed within conventional sheet-piled cofferdams; the deep vent shaft structures were constructed top down with the main station box.

61. Early programme delay arising from ground condition and construction

problems was overcome by a substantial acceleration which included the temporary omission of columns, provision of additional equipment and extensive double-shift working. These measures recovered all the programme time lost and the station was completed and opened to the public five weeks ahead of the contract completion date. A major factor in this achievement was the industrious attitude of the 350 man Chinese workforce who were prepared to work under arduous conditions for long hours. In spite of the potentially dangerous nature of this scale of construction the safety record was good—in 320 000 man days of work there were no fatalities, the accident incidence rate was 3·5% per month, and the working hours lost averaged 1·6%.

62. The completion ahead of time of this complex structure in spite of substantial difficulties could not have been achieved without the flexibility of the design and construct contract, and the close co-operation of Client, Engineer and Contractor.

Design and construction of Tsim Sha Tsui station

63. Nishimatsu Construction Co. were awarded the contracts for Jordan and Tsim Sha Tsui stations, and the running tunnels between. The works are located beneath the southern end of Nathan Road in Kowloon, which is one of the most congested areas.

64. Tsim Sha Tsui station is a two-level (trackbed and concourse) underground station bounded by multi-storey commercial, residential and hotel buildings.

65. Consideration of the geographical circumstances and ground conditions led to an alternative method of construction based on bottom up construction within a contiguous pile cofferdam (PIP-W wall) being adopted instead of the diaphragm wall and top down sequence assumed by the Engineer.

66. The following advantages were envisaged.

(*a*) Difficult and complicated underpinning works in the rock, which existed

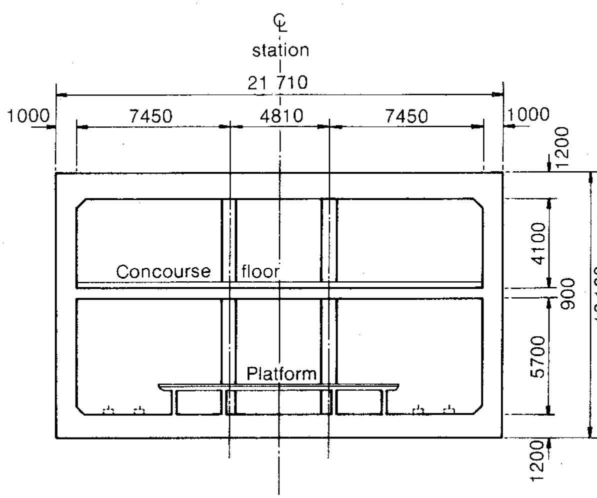


Fig. 11. Tsim Sha Tsui station—typical cross-section (dimensions in millimetres)

above formation level of the entire length of the station, would be avoided.

(*b*) The augured piles would produce less vibration and noise.

(*c*) As the PIP walls would be substantially narrower than the diaphragm walls, the problem of diverting the numerous utility services in the site area would be reduced.

(*d*) The permanent structure could be constructed in drier conditions.

(*e*) The problems of handling the large reinforcement cages required for diaphragm walls within the limited space would be avoided.

(*f*) The period of works construction near adjacent buildings would be reduced, alleviating inconveniences to users.

67. A typical section through the station is shown in Fig. 11. Haunches at the inner corners were designed to allow economical wall and slab thickness. Columns are at 8·4 m centres longitudinally.

68. The permanent works were designed in accordance with CP 110. For soil loading, ϕ was taken as 30° above the concourse floor slab, and 35° below. Design assumptions with respect to water level, building loads etc. were identical to those used for design of the cofferdam walls.

69. The sequence of construction was as follows:

(*a*) base slab
(*b*) haunches
(*c*) columns up to concourse floor slab
(*d*) walls up to concourse floor slab
(*e*) concourse floor slab
(*f*) upper columns
(*g*) upper walls
(*h*) roof slab

70. The wall concrete was cast against the cofferdam PIP walls, or rock, obviating the need for outer shuttering. Transverse construction joints were generally at 25 m centres, resulting in a maximum concrete pour of 1000 m^3.

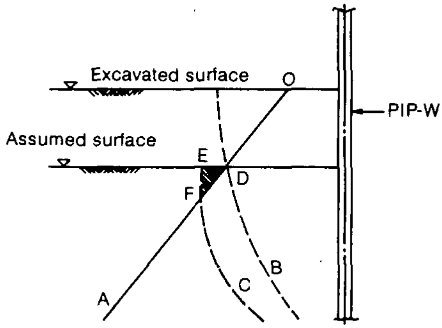
71. The design and construction of the plant room areas was difficult due to the complicated outline of the structures.

Design and construction of the cofferdam for Tsim Sha Tsui station

72. For the design of the PIP cofferdam the following parameters were specified or adopted.

(*a*) Wall stiffness per metre width: $EI = 9{\cdot}40 \times 10^8$ kN cm^2/m
(*b*) Traffic load 14·7 kN/m^2
(*c*) Building load 353 kN/m^2
(*d*) Earth pressure: a trapezoidal loading was assumed for active earth pressure.
(*e*) Water pressure: from 1 m below ground level, full hydrostatic pressure was assumed.
(*f*) Design strength of pile mortar was taken as 23·5 N/mm^2.

73. Excavation was carried out inside the station box, with walings and strutting being erected at predetermined levels to suit the construction of the permanent works. The stresses imposed on the PIP wall, walings and struts at each



A Passive earth pressure (plastic equilibrium)
B Initial elastic horizontal reaction pressure calculated by computer
C Final elastic horizontal reaction pressure calculated by computer

Fig. 12. Tsim Sha Tsui station—earth pressures

stage of excavation were determined by considering their equilibrium with the imposed loads and passive soil resistance by the following sequence of calculations.

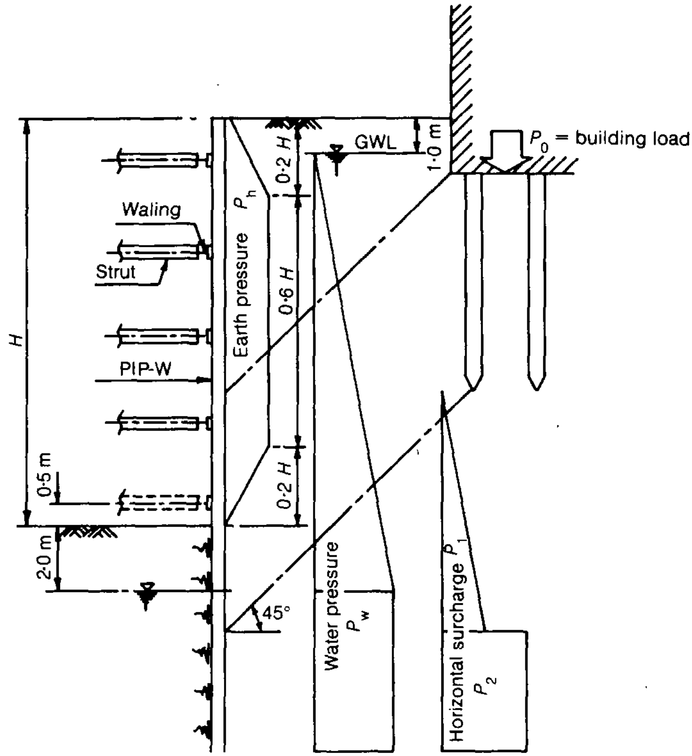
74. First, the initial elastic horizontal reaction pressure, line B in Fig. 12, was calculated by computer using the design loading model shown in Fig. 13, which includes earth pressure, water pressure and building loads. The coefficients of horizontal subgrade reaction used for calculating the passive resistance are shown in Table 3.

75. Secondly, earth pressure for the Rankine passive state (plastic equilibrium) was calculated: line A in Fig. 12.

76. Thirdly, the point was determined where the two curves for the initially computed plastic horizontal reaction pressure and the Rankine passive earth pressure intersected. (Above this point the theoretical elastic horizontal reaction exceeded the theoretical plastic passive resistance of the soil.)

77. Fourthly, the level of the intersection point was taken as an assumed excavation depth, so that the horizontal reaction pressure could be recalculated: line C in Fig. 12. (For this particular calculation, the Rankine passive pressure above the intersection point was subtracted from the combined active earth pressure, water pressure and building loads.) The final reaction pressure used in calculating stresses in the wall, walings and struts was thus defined by line ODE and line C passing through point F (Fig. 12). The error involved in including area DEF was small and could be neglected.

78. The cofferdam was a contiguous bored pile wall based on the PIP pile. The PIP pile is bored with a continuous flight hollow shaft auger mounted on a Kobe P&H 80P crawler (Figs 14 and 15) to the design depth or refusal. As the auger is withdrawn, cement–sand mortar is injected through the auger shaft, leaving a formed mortar pile. A reinforcement cage or H beam is then lowered into the mortar to form a complete reinforced PIP pile.



Earth pressure: $P_h = 0{\cdot}8K_a\bar{\gamma}H$
Water pressure: $P_w = (H+1{\cdot}0)\gamma_w$

Horizontal surcharge from building: $\begin{cases} P_1 = \tfrac{1}{2}K_aP_0\text{(pile friction)} \\ P_2 = K_aP_0\text{(building load)} \end{cases}$

Fig. 13. Tsim Sha Tsui station—design loading model

Table 3. Tsim Sha Tsui station—coefficients of horizontal sub-grade reaction

Standard penetration test N value	K, kg/cm^3	ϕ, degrees
10–20	1·8	30
20–30	2·5	35
30–100	3·5	35
Over 100	4·5	35
Moderately decomposed granite	8·0	–

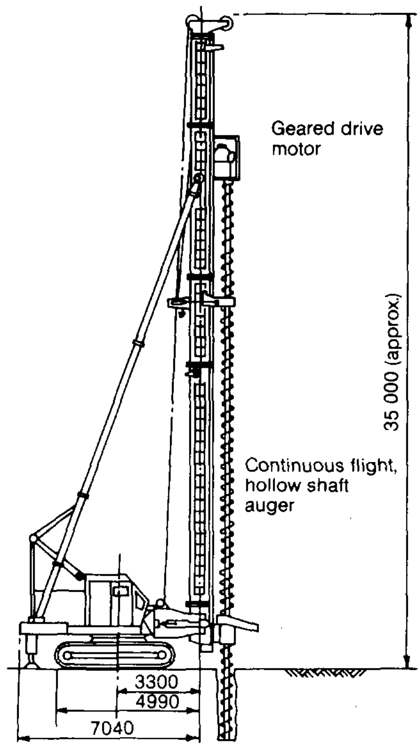


Fig. 14. PIP-W piling rig (dimensions in millimetres)

79. To form a contiguous pile (PIP–W) wall, PIP piles (A piles) are formed in alternate pile positions in the manner described in § 78. The infill piles (B piles) are then constructed in the same way as the A piles, except that during the auger withdrawal and mortar placement, a high pressure plunger pump (200 kg/cm^2) is used for injecting cement paste through the pile, which effects a vertical mortar cut-off between the B pile and two adjacent A piles. The sequence is illustrated in Figs 16 and 17.

80. When boulders are encountered, or for drilling through rock, the auger is replaced by a Koken N-50 Big Man rock-boring machine. The pre-augured length of hole in the soft ground is filled with bentonite to prevent the wall from collapsing.

81. For the cofferdam for Tsim Sha Tsui station the piles had to support the temporary traffic deck at road level, and also had to be underpinned in the rock to enable excavation to be carried down to formation level.

82. To meet these apparently conflicting requirements the piles, which were 450 mm dia. at 500 mm centres, were of three types. Type A piles were first constructed by drilling through the rock to a distance of 500 mm below the bottom of the base slab of the station. Every sixth pile is a type A pile (Fig. 18) and these piles were used to support the temporary traffic deck. In between each two type A piles, two type B

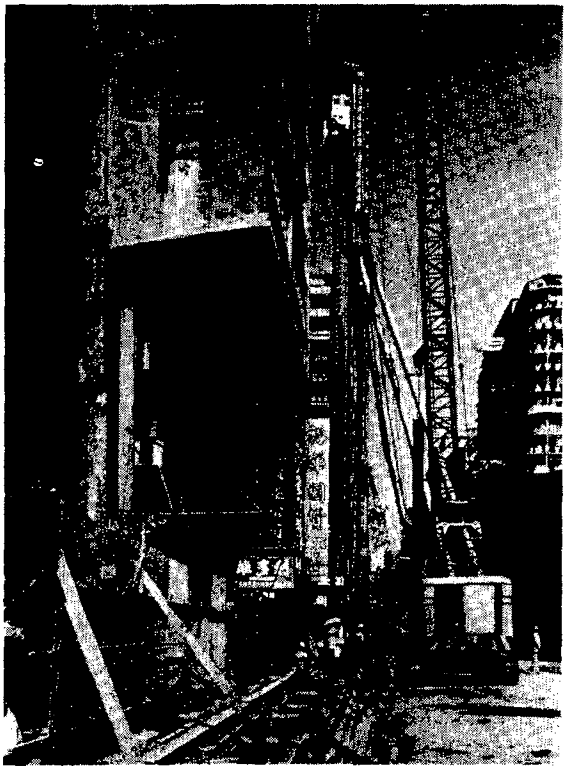


Fig. 15. PIP-W piling rig

piles were constructed, but these piles were only keyed into the bedrock to a distance of 1500 mm from the rockhead level. Type C piles were then cast between all the type A and B piles and injected to form a mortar cut-off as described in § 79. The type C piles rested on the rockhead. The type A and B piles are reinforced with 300 mm × 300 mm H steel (SS41, JIS G3101), while the type C piles are reinforced with a reinforcement cage made up of ten 25 mm dia. bars.

83. Between the longitudinal cofferdam walls, two lines of piles at 3 m centres at the third points were constructed in the same way as the type A piles to provide support for the temporary traffic deck (Fig. 19). These piles were also used to stiffen the struts for the cofferdam against buckling.

84. The mix proportions, per unit weight of mortar, used for PIP construction were as follows:

cement	782 kg
sand	876 kg (sand/cement ratio 1·12)
water	415 kg (water/cement ratio 0·53)
intrusion aid (grout fluidifier)	6·84 kg (intrusion aid/cement ratio 0·008 75)

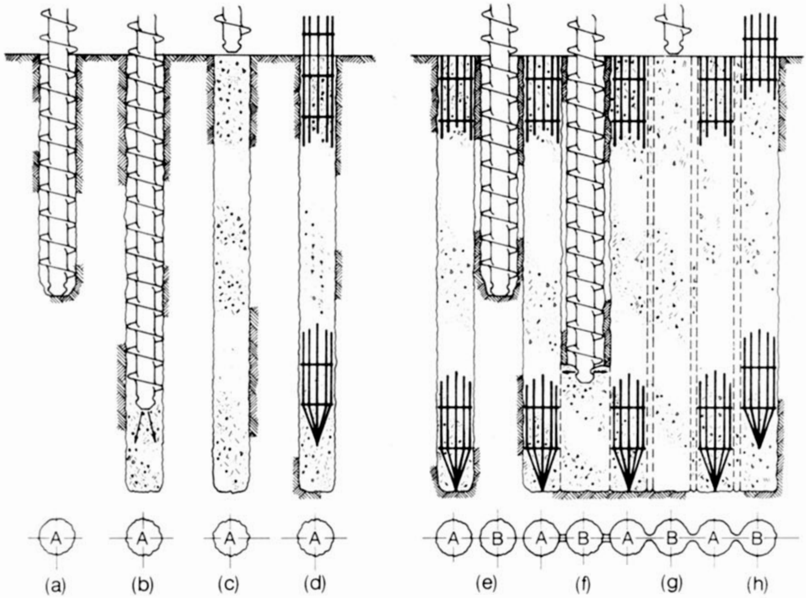


Fig. 16. PIP-W piling procedure for A and B piles: (a) auguring; (b) withdraw auger and inject mortar; (c) completion of injection; (d) insert reinforcement cage or H shape; (e) auguring; (f) withdraw auger, inject and jet mortar; (g) completion of injection and jetting; (h) insert reinforcement cage or H shape

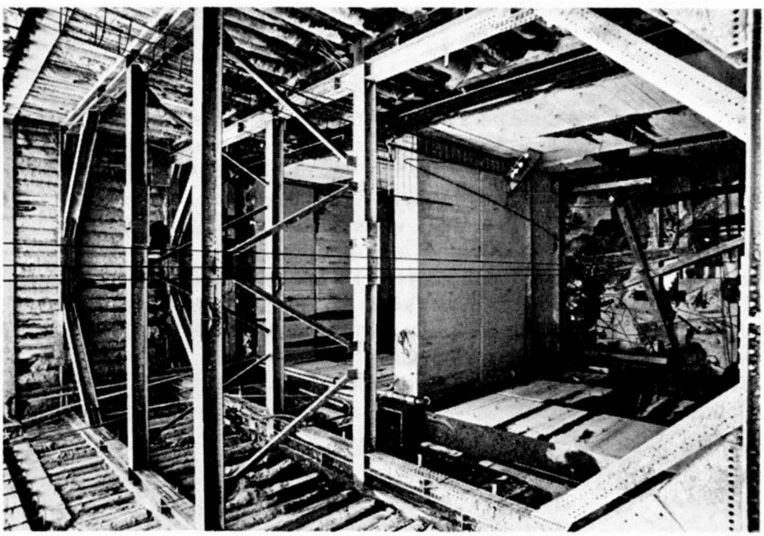


Fig. 17. PIP-W piling walls

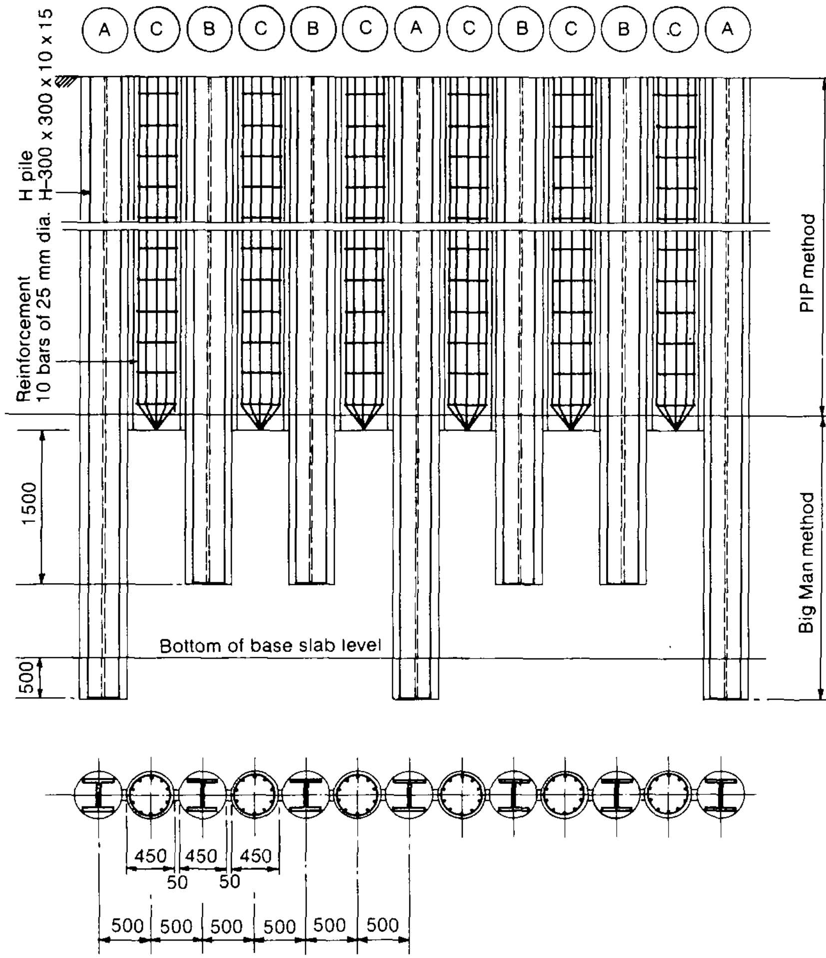


Fig. 18. PIP-W piling walls with A, B and C piles (dimensions in millimetres)

85. The strutting and waling was constructed using H steel at 2·1 m intervals to suit the station columns at 8·4 m centres. Six levels of frames were installed and the struts were preloaded immediately after installation to ensure effective frame fit. The traffic deck comprised 2000 mm × 750 mm steel Sumi-deck with an anti-skid surface treatment.

86. Verticality of the piles was of the utmost importance and a severe tolerance of 1 : 200 was specified.

87. The specified verticality was satisfactorily achieved except in one area where the PIP auger rig could not be used due to the restricted headroom imposed by an overhanging building. Here the entire length of the pile had to be constructed by

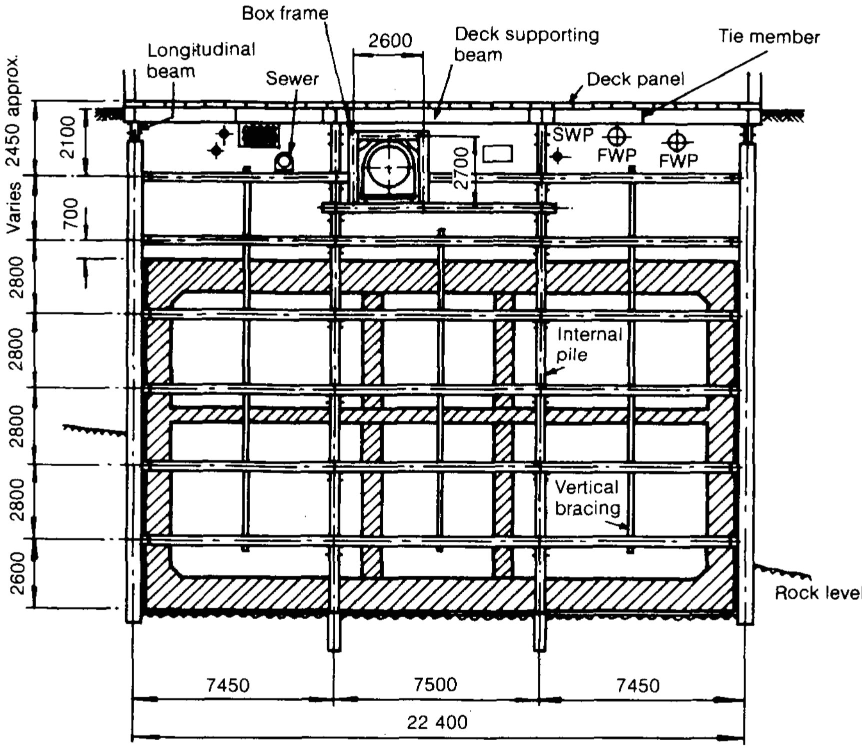


Fig. 19. Tsim Sha Tsui station—typical cross-section, showing temporary deck support (dimensions in millimetres)

using the rock-boring machine, and the H steel in the type A and B piles, and reinforcement cages in the type C piles, which could not be inserted in one operation, required a number of intermediate joints.

88. The construction method adopted proved to be successful, with the works being constructed as originally planned and the basic station structure completed nine weeks ahead of the original programme.

89. A problem was encountered due to unexpected lowering of the groundwater table outside the cofferdam walls, caused by ingress of water into the excavation through fissures in the rock. Fortunately, the adjacent buildings were modern and founded on load-bearing piles to rock, and were therefore generally unaffected.

90. This method of construction is now being employed on the largest contract on the Tsuen Wan extension of the railway now under construction, involving the construction of three stations, one of them a three-level station. Further refinements to the design and construction techniques are therefore being undertaken.