03 May 2013, 1:25 pm - 1:50 pm

The Design and Construction of a Fast Track 16 Hectare, 18 m Deep Basement in Soft Clay in Singapore

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April 29 - May 4, 2013 CHICAGO
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THE DESIGN AND CONSTRUCTION OF A FAST TRACK 16 HECTARE, 18M DEEP BASEMENT IN SOFT CLAY IN SINGAPORE

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ABSTRACT

Singapore's newest integrated resort, Marina Bay Sands, was completed in record time and has garnered numerous engineering awards. The development sits on recent sand reclamation, which in turn rests on deep soft marine clay deposits. With an average excavation depth of around 18 meters, the 16 hectare (39 acre) waterfront development involved some of the largest marine clay excavation in Singapore. About 2.8 million cubic meters of fill and marine clay were excavated from the site equating to about 800 trucks a day for two years.

To overcome the challenges of the bulk excavation and minimize shoring in difficult soil environments, innovative excavation solutions were developed to enable an accelerated construction timetable for this project involving densely packed site works with complex staging and interface issues. These included the use of unsupported circular excavations up to 130 meters in diameter and continuously reinforced 1.5 meter thick diaphragm walls acting in shear. To add to the challenge, a 35 meter deep 'cut and cover' tunnel next to the Singapore's longest bridge, the Benjamin Sheares Bridge, was required. To enable the bridge to tolerate the inevitable imposed lateral displacements of an abutment, the structural system of the existing bridge was modified to allow it to safely articulate in plan.

INTRODUCTION

Marina Bay Sands Integrated Resort is a 16 hectare tourist resort development which includes three 55 story hotels with a connecting sky-park, a casino, a state of the art convention centre (MICE), an art science museum, theatres, retail outlets and floating pavilions. As shown on Figure 1, the west and northern perimeter of the site is bounded by the sea, while the eastern side is interfacing with the existing East Coast Parkway highway (ECP) and the Benjamin Sheares Bridge (BSB).

The development is sitting on reclaimed land, comprising sand infill overlying deep soft clay marine deposits, above an underlying very stiff-to-hard Old Alluvium (OA) layer. The soft marine clay, coupled with the proximity of the East Coast Parkway highway and the Benjamin Sheares Bridge, posed significant challenges to the design of the excavation works (Figure 2).

MBSIR involved some of Singapore's largest excavations, with overall some 2.8 million cubic meters of fill and marine clay being taken from the site, equating to about 800 trucks a day for two years. In addition, a 35 meter deep cut-and-cover tunnel had to be engineered for the construction of Singapore Mass Rapid Transit (SMRT) next to the Benjamin Sheares Bridge, which links the island's east and west coasts and had to remain operational throughout construction.

With more than 40% of the concrete construction occurring between 18 and 35 meters underground, the required timetable was only made possible by innovative approaches to the excavation. These innovations included constructing a 100 meter diameter and two 120 meter diameter circular cofferdams, a twin-cell 75 meter diameter cofferdam and a 130 meter diameter semi-circular cofferdam. In addition, a T-shaped diaphragm wall and modification to the Benjamin Sheares Bridge to ensure the bridge could safely tolerate the horizontal movement imposed upon it. Continuously reinforced concrete shear walls constructed using diaphragm wall panels were also required at this part of the site.

Initially there was only one access to the site and partial top down excavations were required to enable the timely construction of a central haul road across partially completed basements.

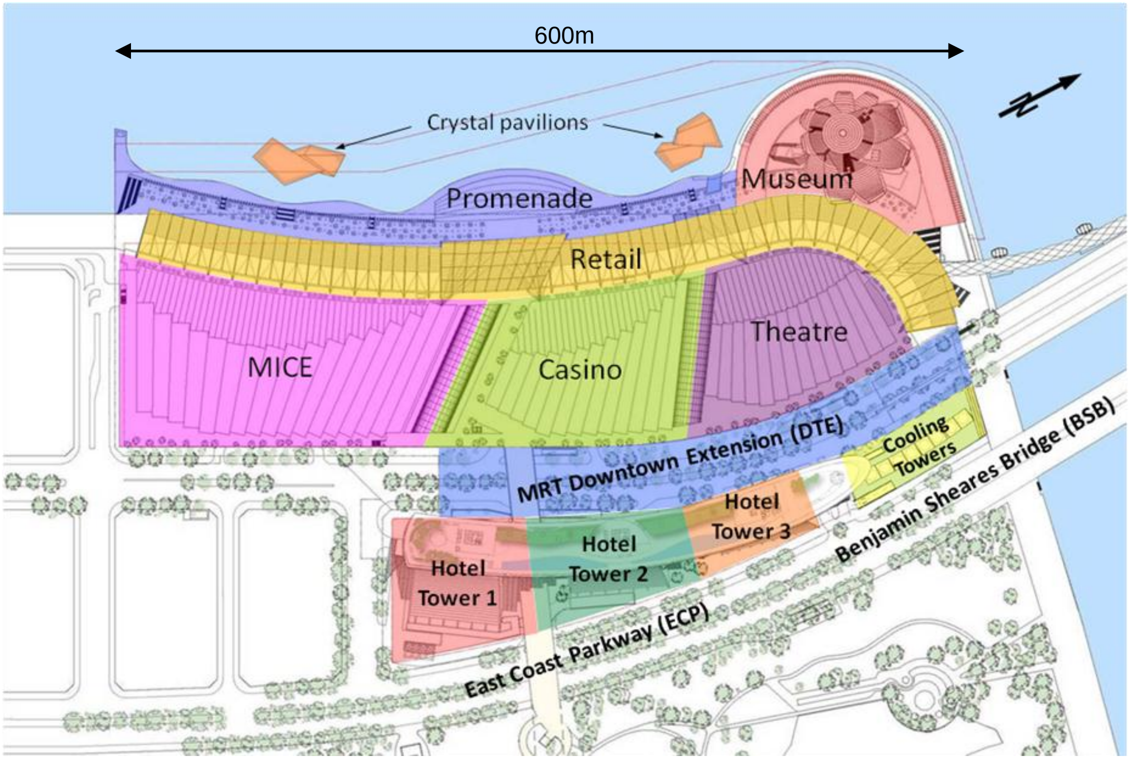

Fig. 1. Overall Development at Marina Bay Sands Integrated Resort.

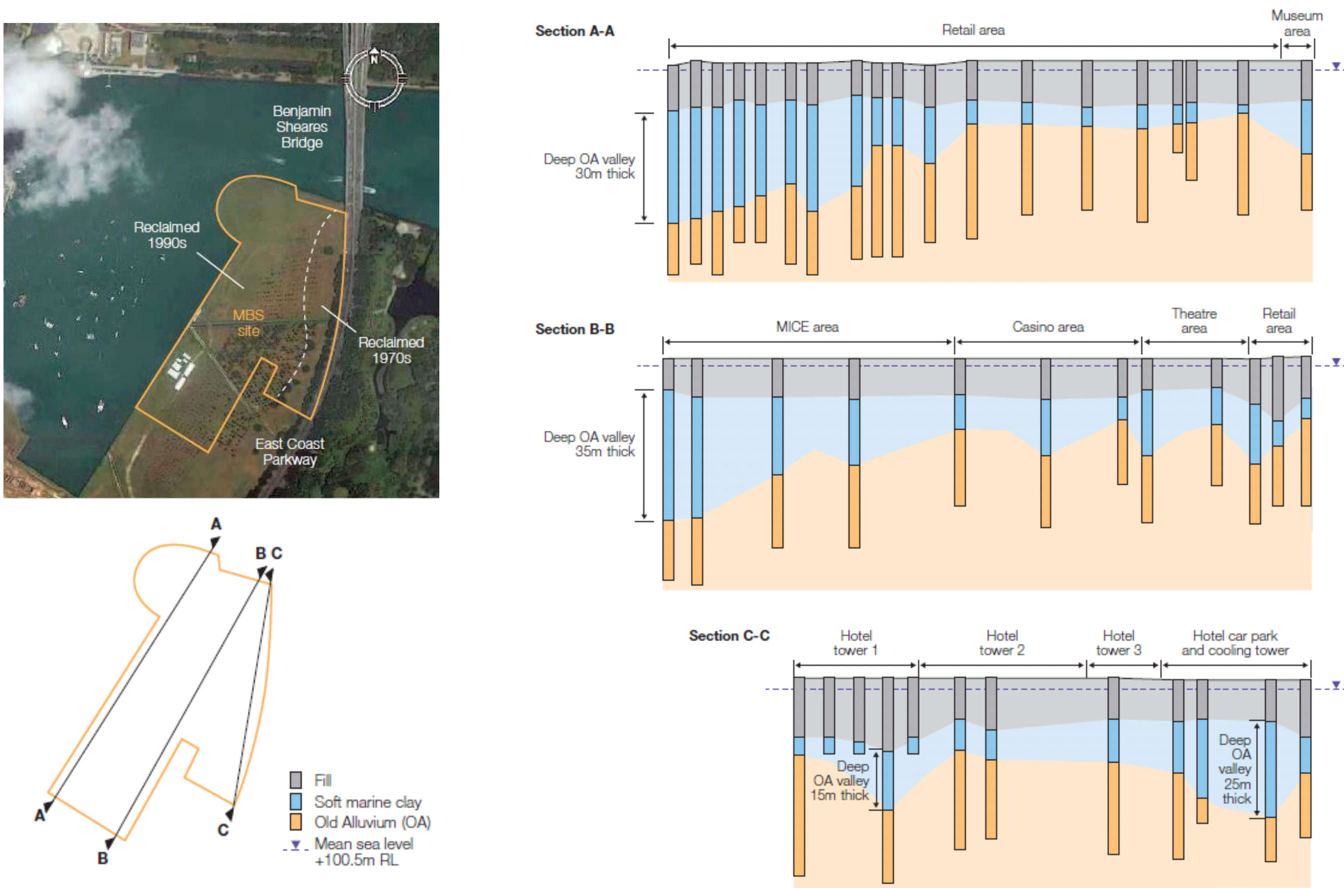

Fig. 2. Site location plan and geological profile.

The haul road allowed access to the 6 basement excavation contracts that were occurring concurrently within the overall site. It was also important that the design allowed these individual contracts to proceed without hindering adjacent contracts.

SITE GEOLOGY

Reclamation History

Over the past decades, the Marina Bay area has undergone several reclamation phases with the latest being completed in mid 1990's. As shown in Figure 2, the majority of the development is sitting on Phase VIII (1990's) reclamation zone, while the eastern side is located within the Phase VB reclamation zone, completed in late 1970's.

Ground Conditions

Ground level across the site is generally flat at about +103 to +103.5mRL, with the recorded groundwater table being at approximately +100.5mRL. The subsoil conditions typically comprise 12 to 15m thick of reclamation Fill overlying 5 to 35m of Kallang Formation soils, underlain by the stiff to hard Old Alluvium. The Kallang Formation consists of predominantly soft marine clay, with some interbedded firm clay and medium dense sand of fluvial origin (Figure 2).

In the main podium area which covers the MICE, Casino, Retail, Theatre and Museum, a thick marine clay deposit (up to 35m) is generally encountered on the southern end and it gets thinner towards the northern end (Geological Sections 1 & 2). On the eastern side, where the Hotel and DTE are located, the soft marine deposit is approximately 10m thick, except at the northern and southern end where deep Old Alluvium valleys are encountered (Geological Section 3).

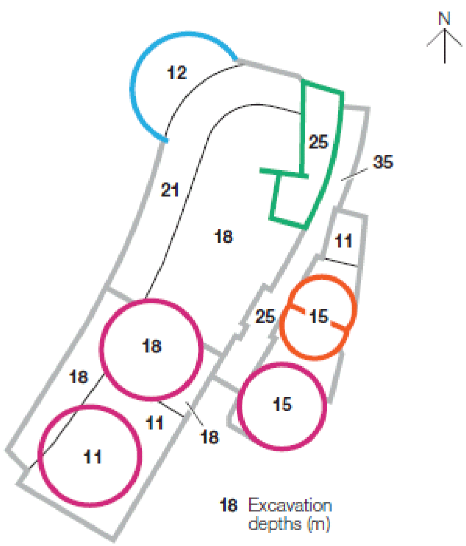

Fig. 3. Excavation plan with depths.

CIRCULAR DIAPHRAGM WALLS FOR MINIMAL STRUTTING

Deep excavations were required across the site with general excavation depths ranging from 18m to 35m underground (see Figure 3). To overcome the challenges of the bulk excavation and minimize shoring in the difficult soil environment, the excavation design included four large reinforced concrete cofferdams (see Figure 4) comprising:

1. two circular, 120m diameter, cofferdams in the Expo and Convention Centre (MICE) area,
2. one circular, 103m diameter cofferdam and a 75m diameter twin-celled cofferdam in the Hotel area, and
3. one semi-circular, 130m diameter, cofferdam in the Museum area.

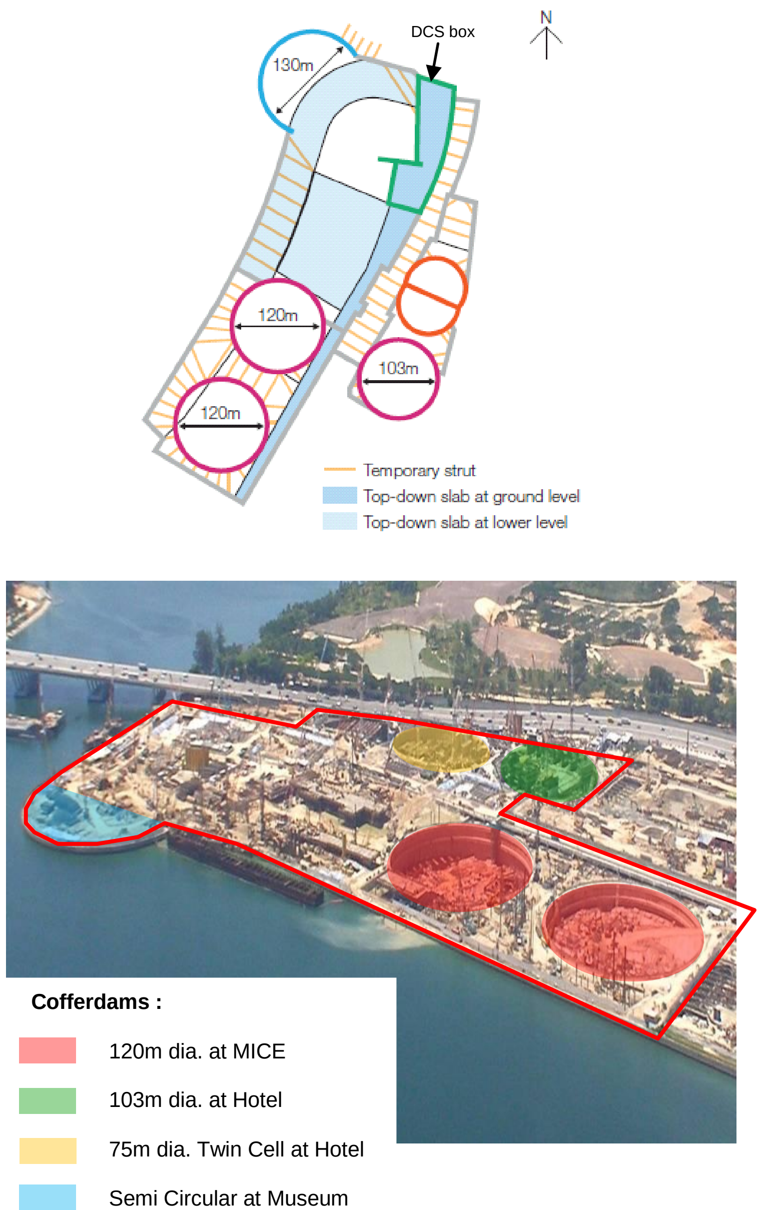

Fig. 4. Excavation plan and location of circular cofferdams.

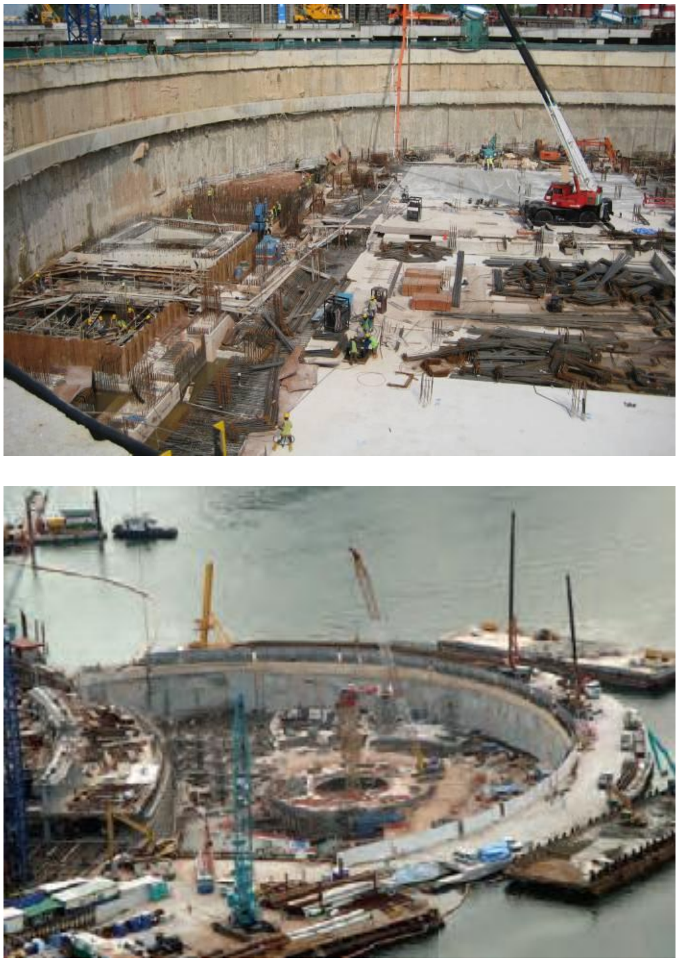

Fig. 5. Areal view of excavation inside a 120m cofferdam and the 130m semi circular cofferdam.

Each circular cofferdam was a dry enclosure, within which excavation and subsequent construction could be carried out without the need for conventional temporary support. The hoop compression forces within each cofferdam provide an open underground space which allowed a prop-free environment for the substructure works to be carried out. Apart from the cost savings in steel, elimination of struts reduced congestion and therefore allowed the work to be accelerated (Figure 5). The only constraint was that excavation within a cofferdam must be deeper than the excavation outside of it.

The 120m diameter cofferdams were among the largest ever deployed in Singapore generally, and notable for their excavation depth – down to 18m below ground. They allowed work to progress across the site simultaneously with either the excavations to north or south being able to be in advance of the other. Three dimensional analyses were carried out to demonstrate this flexibility (see Figure 6).

The 130m semi-circular cofferdam relied on the adjacent wall to the south and ground anchors to the north for its lateral stability at each end. In addition significant shear forces were generated within the final few panels that required the development of friction across the vertical panel joints.

The design of the MICE cofferdams in conjunction with a steel truss system to the perimeter diaphragm walls at the MICE area allowed independent excavation between the MICE area and the Casino and Theatre areas to the north. The single-layer steel truss / strut system (see Figure 7) enabled the 11m deep excavation to be completed outside the two cofferdams in the MICE area.

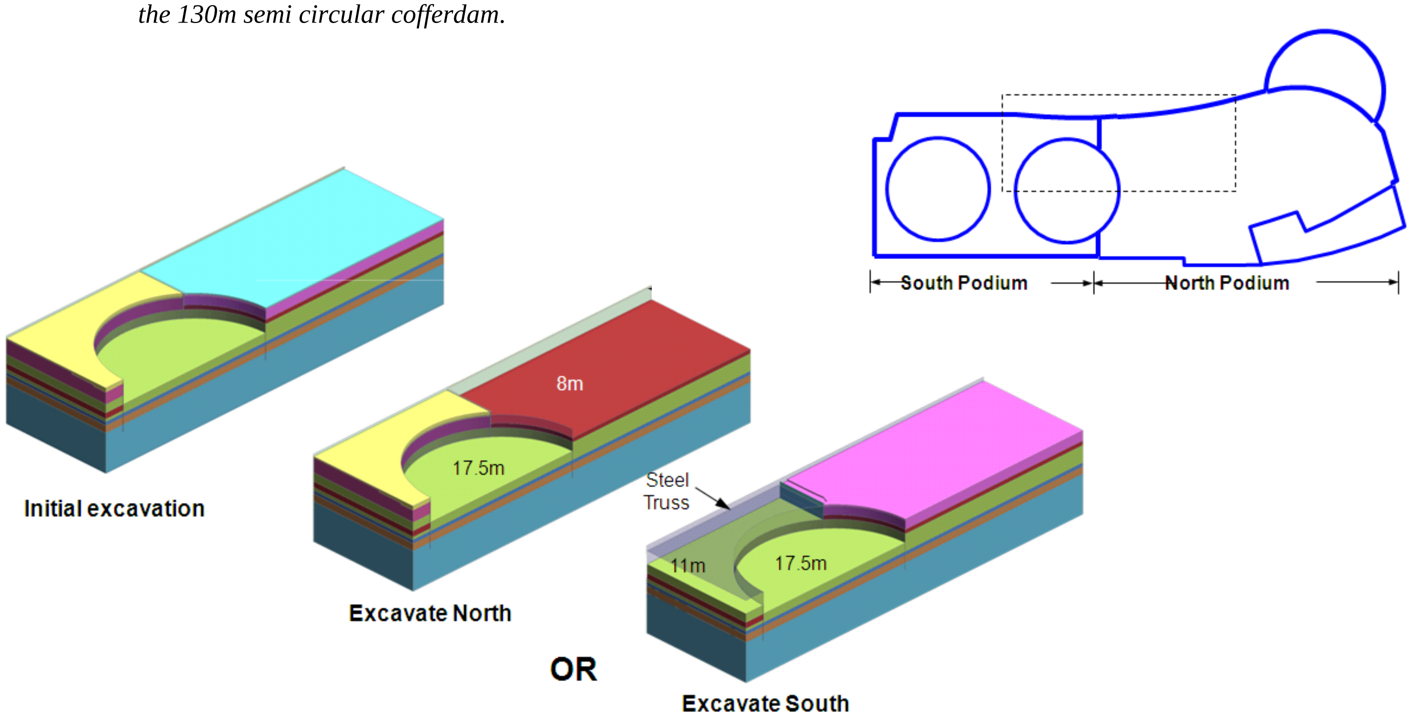

Fig. 6. Analyses to demonstrate construction flexibility.

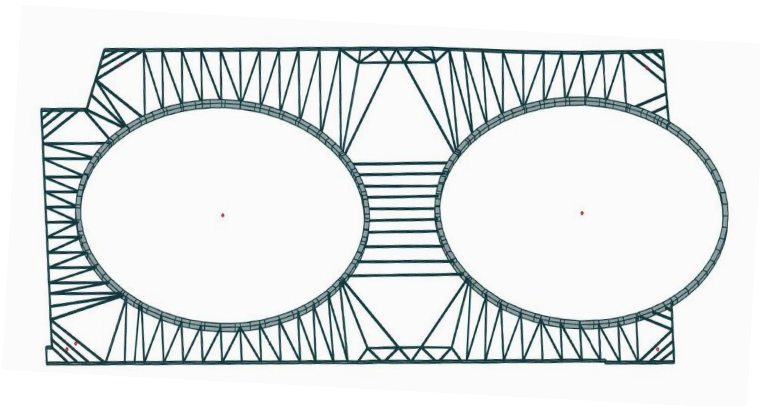

Fig. 7. Isometric view of analysis model of MICE truss support at +100mRL.

Due to the vicinity of the East Coast Parkway, the use of the twin cell diaphragm wall cofferdam, without any crosswall above excavation level, enabled unhindered bulk excavation (see Figure 8). In a similar fashion to the semi-circular cofferdam, significant shear stresses were induced in the cross wall which was designed to be resisted by friction across the vertical joints between panels.

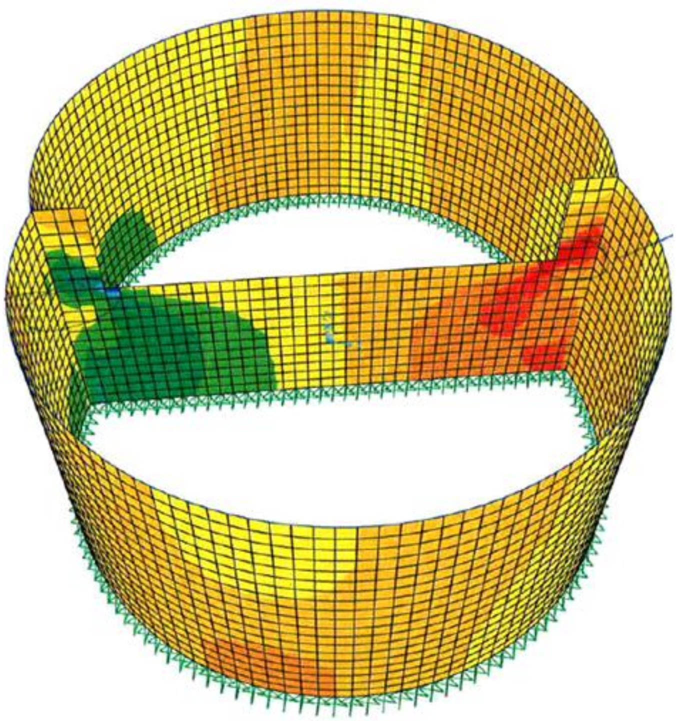

Fig. 8. SAP analysis shear stress in the twin cell cofferdam.

Parts of the diaphragm walls of the two Hotel cofferdams doubled as permanent hotel basement walls and load bearing elements for the Hotel towers. The remaining parts of these walls, and both the 120m diameter cofferdam diaphragm walls in the MICE area (shown as red in the plan on the upper part of Figure 9), had to be removed down to the excavation level by "wire cutting" them into liftable blocks before removal.

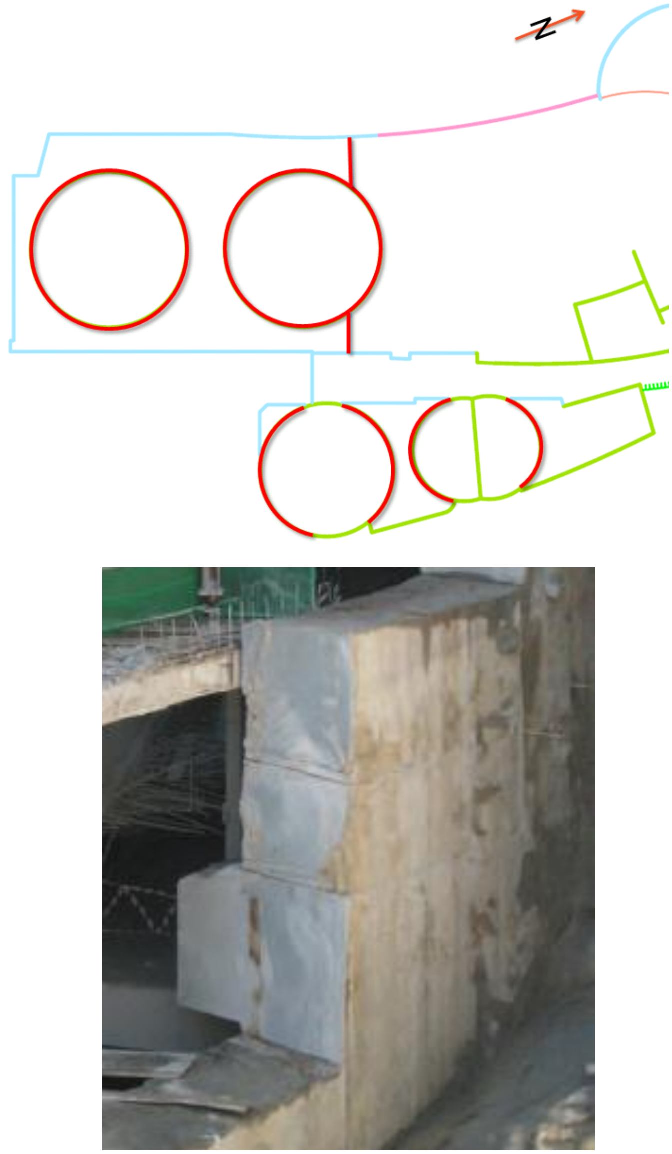

Fig. 9. Locations of wall removal (in red) and cutting of the diaphragm wall exposed above excavation level.

TOP DOWN CONSTRUCTION AT CASINO AREA

As the layer of soft marine clay is generally thinner in the northern part of the site, a top-down excavation method with minimum temporary supports was used to facilitate the 4 level basement construction in the Casino area in conjunction with simultaneous strutted excavation in the adjacent cut-and-cover SMRT tunnel (DTL). After various considerations, it was decided that the most practical way forward was to design the B2 slab to act as a continuous support between the two retaining walls on the western and eastern sides, which then allowed excavation to B4 and construction of substructure below B2 and superstructure above B2 to proceed concurrently. Considerable time savings was achieved by allowing these two activities to go on simultaneously. The construction sequence for this area is shown in Figure 10.

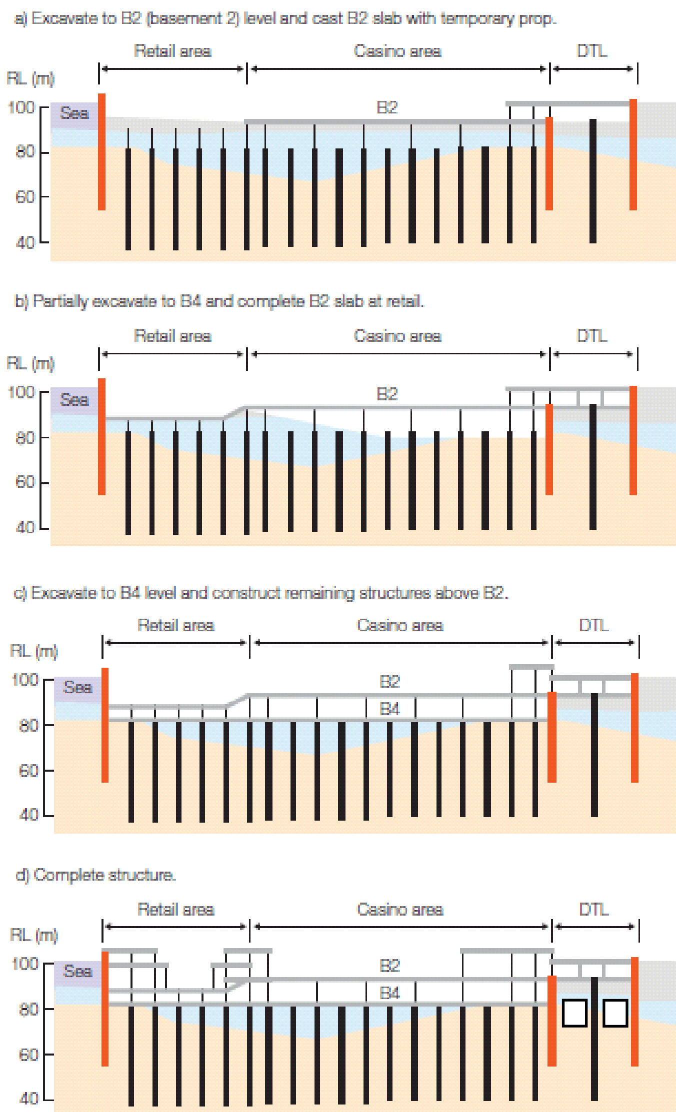

Fig. 10. Construction sequence at Casino area.

CONTINUOUSLY REINFORCED DIAPHRAGM WALL FOR DCS BOX

For energy efficiency, the Singapore Government required the inclusion of a District Cooling System (DCS), its plant housed in a deep reinforced box in the northern part of the site (see Figure 11). Shear walls constructed with the DCS box enabled unhindered bulk excavation across the Theatre area to the west. Within the DCS box, a "top-down" excavation method within minimum temporary strutting was used. The DCS box also doubled as a retaining structure for the deepest excavation in the adjacent cut-and-cover tunnel where a deep valley of soft marine clay is present. As the Theatre structures are isolated from the remainder of the development, the DCS box has to permanently support the lateral loads coming from the ground to the east of the DTE tunnel.

Fig. 11. View showing location of DCS box and Theatres.

The large shear forces required to be transferred into the underlying Old Alluvium require continuously reinforced diaphragm walls. To achieve this support, three east-west shear walls were constructed from diaphragm walls at the locations indicated in Figure 12.

Each shear wall is 1.5m thick by 50m long (approximately) and comprises a series of female panels (3.0m) and male panels (6.4m). To ensure structural continuity, the shorter female panels are cast with steel end plates on both ends, leaving about 1.5m of reinforcement bars un-concreted at each end for future lapping with the subsequent male panel reinforcement as shown in Figures 13 and 14.

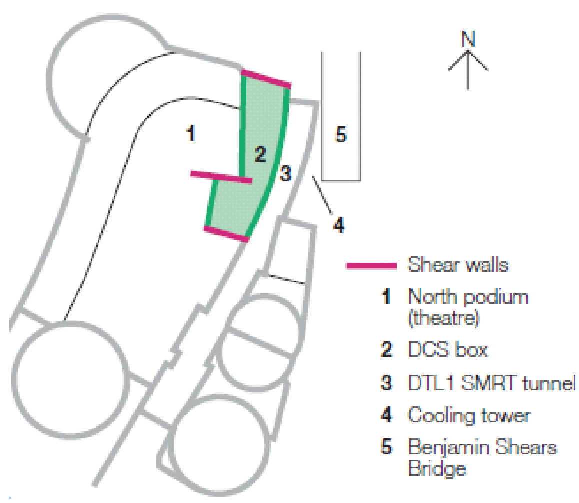

Fig. 12. Shear wall locations in the DCS area.

The general design principle used to ensure the lateral load transfer from the shear walls into the underlying Old Alluvium is illustrated in Figure 15. Movement predictions across the DCS were made using 2 dimensional Plaxis analyses where the shear wall effect was modeled as a strut supporting the floor plates of the DCS (see Figure 16).

Fig. 13. Reinforcement for a female panel

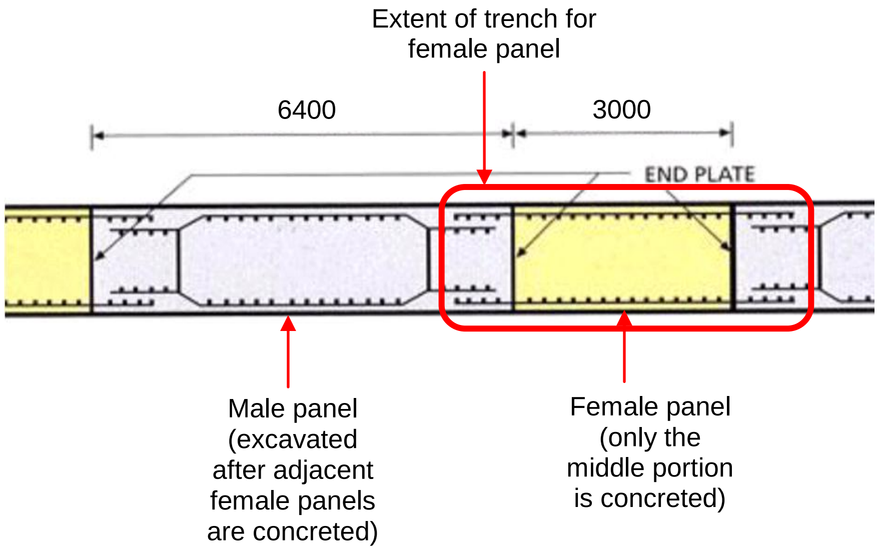

Fig. 14. Plan showing male and female panel layout.

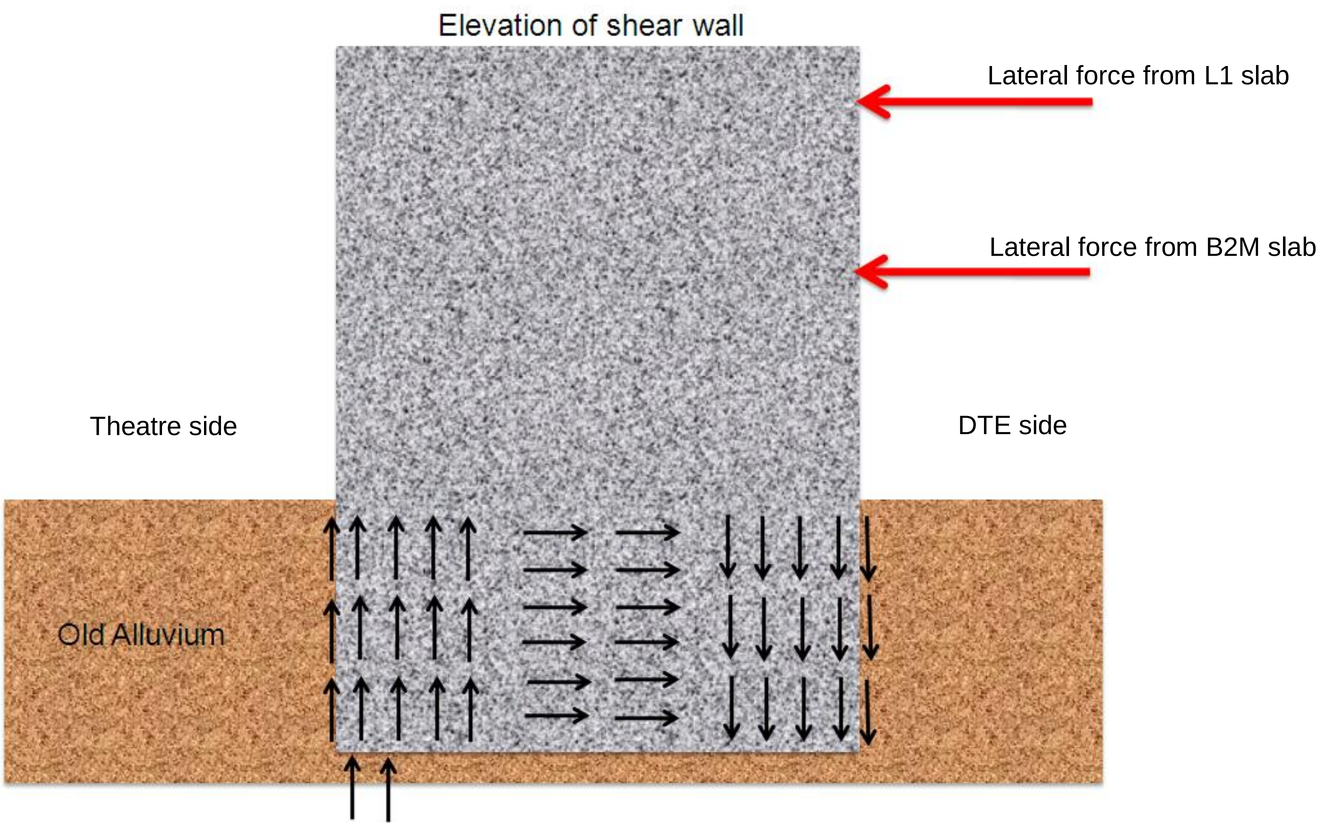

Fig. 15. Shear and end bearing reaction from Old Alluvium acting on the DCS shear walls.

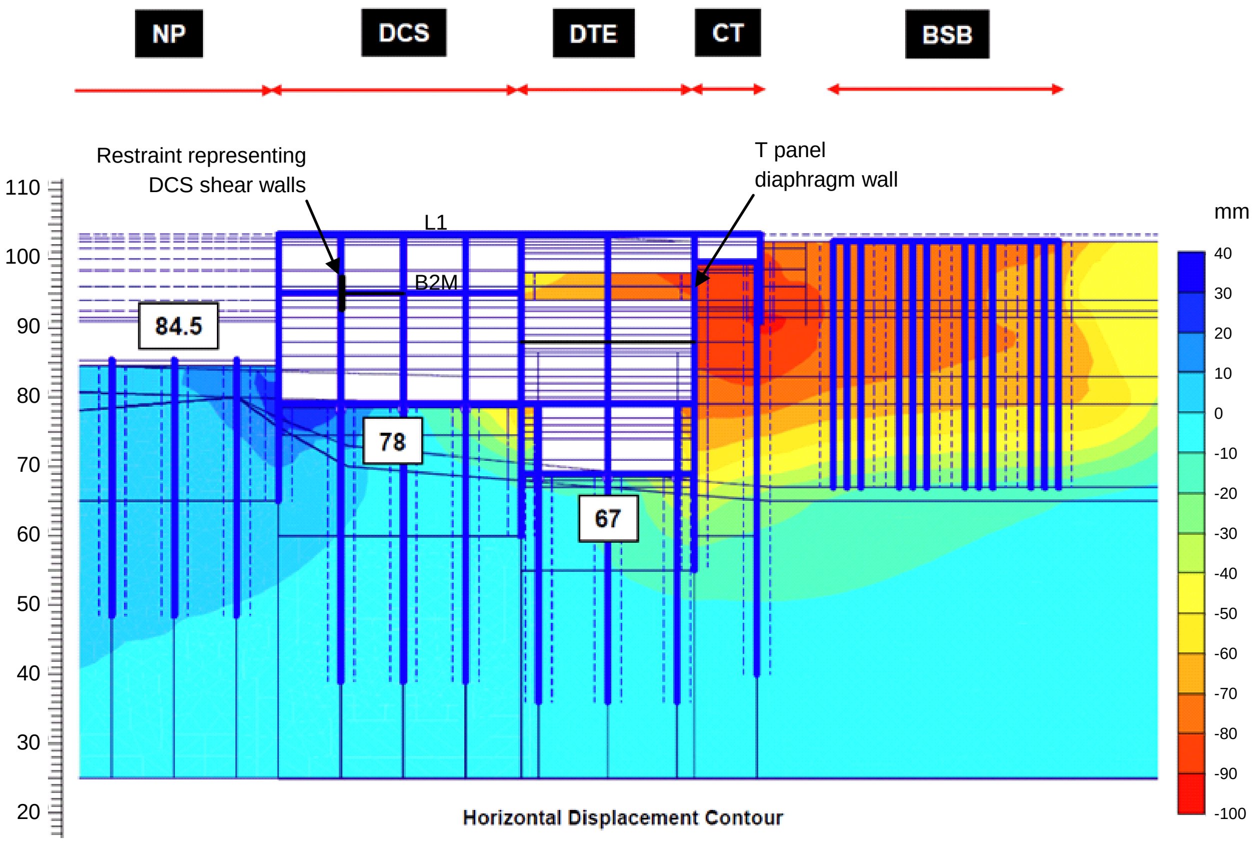

Fig. 16. Plaxis analysis of the excavations in the DCS box and adjacent areas.

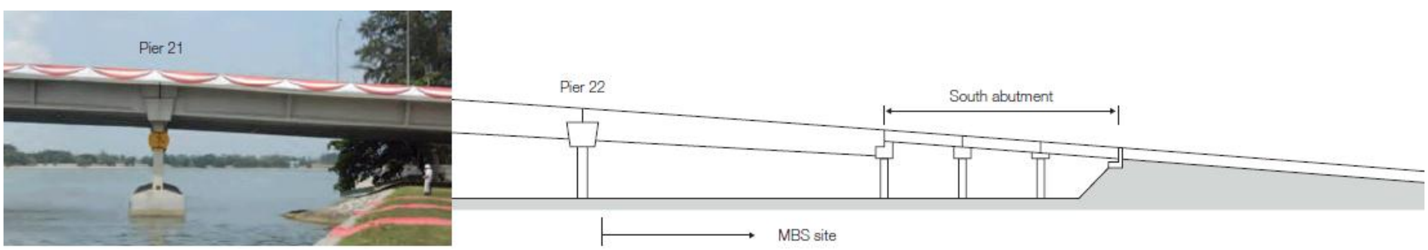

Fig. 17. Elevation of south end of the Benjamin Sheares Bridge.

MANAGING THE IMPACT OF THE EXCAVATION WORKS ON THE BENJAMIN SHEARES BRIDGE

Excavation within the deeper end of the cut-and-cover SMRT tunnel was carried out adjacent to the operational Benjamin Sheares Bridge (BSB) as shown in Figures 17 and 18. Movement control became critical. To limit the impact of excavation works on the bridge, a stiff temporary strutted T-shape diaphragm wall was installed and as explained earlier, the DCS box was also designed to resist lateral earth pressure coming from the east of the MRT tunnel. Despite using these stiff retaining systems, calculations showed that the predicted lateral movement imposed onto the ground under the bridge abutment, shown in Figure 16, while not affecting ride comfort, would overstress the shear connections between the piers and the deck.

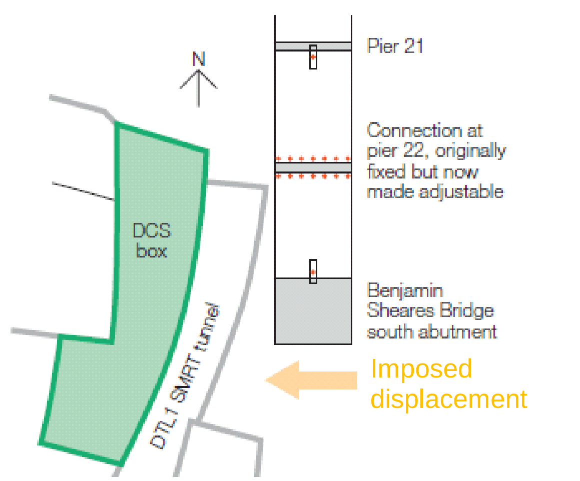

Fig. 18. Plan of south end of the Benjamin Sheares Bridge.

Rather than attempting to stiffen the earth retaining system further, which could lead to an uneconomical and impractical design, the existing fixed shear pins between the deck and the southernmost pier were replaced by three adjustable, pins (see Figures 19 and 20). As two pins were sufficient to resist vehicle braking loads, periodic individual adjustment of these pins enabled the last section of the bridge deck to articulate in plan and render the whole bridge tolerant of the ground movement inevitably caused by the deep excavation for the development and the SMRT tunnel. On-going monitoring throughout the excavation enabled comparisons with design predictions and timely adjustment of the shear pins.

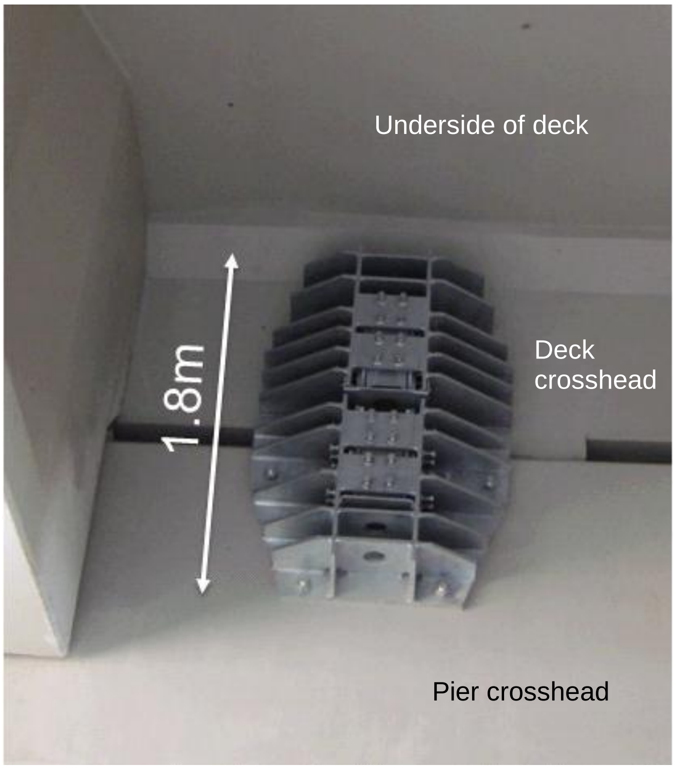

Fig. 19. View of adjustable pin connection.

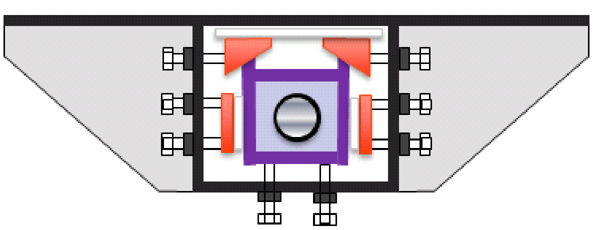

Fig. 20. Plan showing adjustment bolts

USE OF PERMANENT UNDERSLAB DRAINAGE

An underslab drainage system was designed to relieve the lowest basement slabs of uplift water pressure, and thereby negate the need for hold-down tension piles. The system was installed in the north cofferdam beneath part of the MICE facilities together with the north Retail, the Casino, the Theatres, the Museum and the DCS as shown in Figure 21.

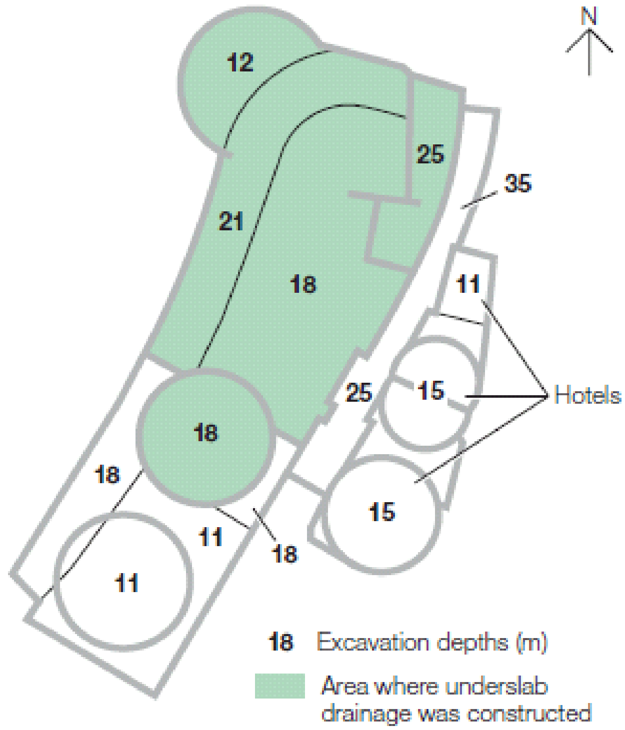

Fig. 21. Plan showing extent of underslab drainage.

The system typically comprises a drainage blanket formed of 20mm single-size aggregate, perforated pipes, perimeter gutter drains, piezometers, sump pumps and pressure relief wells (Figure 22). The seepage groundwater collected by the system is discharged into the public drainage system outside the site.

To ensure satisfactory performance throughout its design life, the MBS drainage system requires periodic maintenance and monitoring of the groundwater pressure beneath. The design team prepared a monitoring and maintenance manual that include replaceable piezometers. Should the underslab drainage system malfunction under the worst scenario, contingency measures such as opening inspection covers to relieve uplift pressure, installing additional pressure relief wells, and deploying additional surface pumps can be put into effect before remediation works are done.

It should be noted that while these types of schemes are relatively common in many places they are rarely allowed in Singapore due to the lack of confidence in future owners to continue with the rigorous ongoing monitoring scheme. For this particular project, however, it could be demonstrated that the underlying Old Alluvium is relatively clayey and consequently having low permeability. It could also be readily shown that the program savings by adding this scheme were substantial.

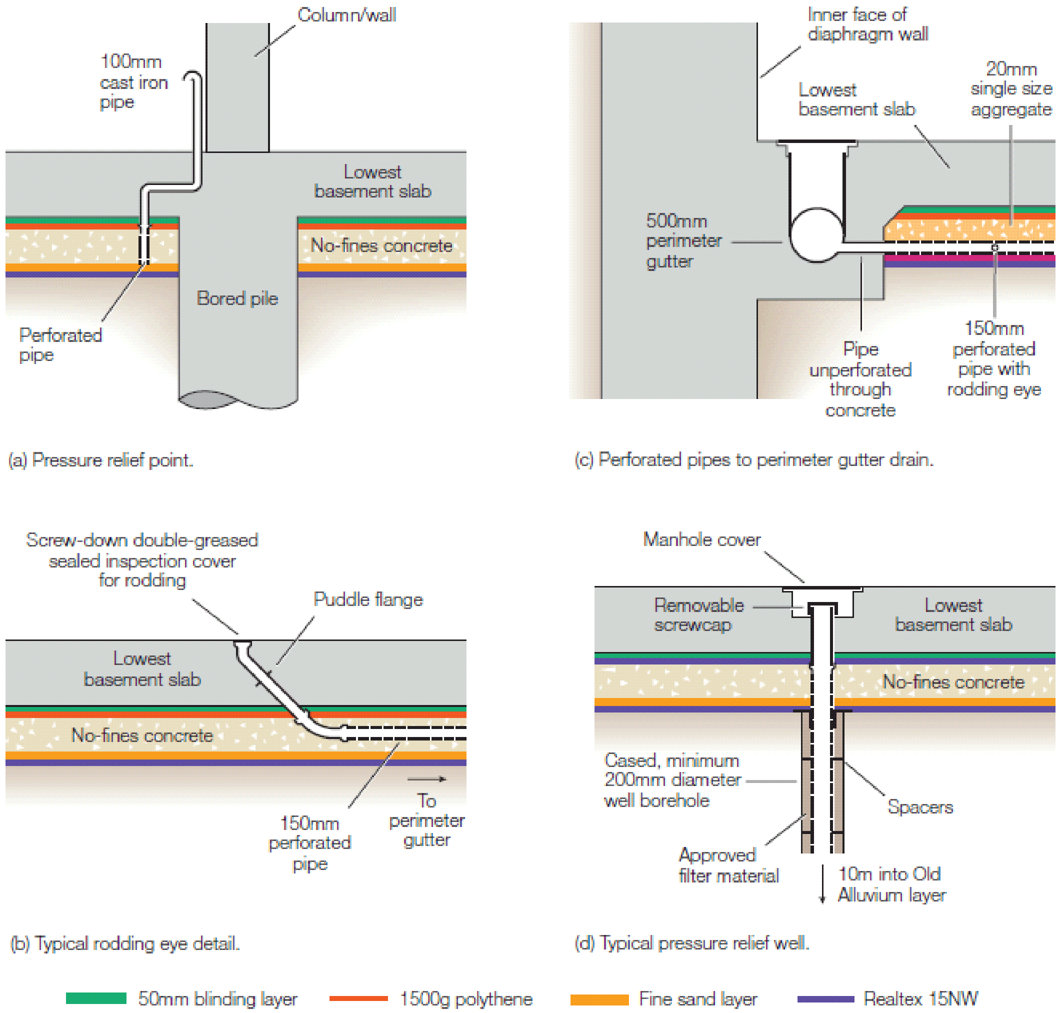

Fig. 22. Sub-systems forming the underslab drainage system.

OVERVIEW

The basement structure was completed in 2009. Innovative approaches to the excavation design in these difficult site and time constraints set a benchmark for future large-scale excavations both within Singapore and elsewhere.

ACKNOWLEDGEMENTS

The design for this project was clearly a major undertaking involving many parts of Arup and the ongoing assistance of many of my geotechnical and structural colleagues is gratefully acknowledged. Special mention must go to Henry Shiu, Seven Yau, Erin Leung and Wing Kai Leong of Arup Hong Kong, David Vesey of Arup London and Khine Khine Oo, Philip Iskandar, Wijaya Wong and Chia Wah Kam of Arup Singapore. The overall Project Director for Arup, Va-Chan Cheong, and the Client's Project Manager, Mike Barton, both played a crucial role in the timely delivery of the geotechnical aspects of the project.