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A customised earth retaining system for deep excavation works

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ABSTRACT: A world-class new cultural and arts centre of Singapore, Esplanade - Theatres by the Bay, is currently under construction. A customised 11-m free-standing earth retaining system consisting of an integrated diaphragm wall with buttress wall supports and improved jet-grouted soils has been adopted for the deep excavation works of the 11m-deep basement construction in soft Marine Clay. The lateral stability and rigidity of this unique excavation support system has been enhanced by the arching action of the retaining system, which is mobilised through basement slabs cast along the perimeter of the semi-circular frame of the basement. Ground deformations and wall movements were closely controlled and kept to a minimum with careful sequence of construction utilising this support system. This paper describes this excavation support system for the deep excavation works, as well as the observed field performance of the system, leading to the successful construction of the basement.

1 INTRODUCTION

In Singapore, much of the land is low-lying and underlain by soft soils of low strength and high compressibility. Deep excavation in such soils is often associated with potentially large ground movements and stability problems. These ground movements, if not restrained initially and are allowed to continue, are irreversible and will further induce more movements. This could possibly result in substantial damage to adjacent structures.

Site control against ground movement is therefore an essential part of the planning, design and construction of deep excavation works in an urban environment like Singapore. Timely field instrumentation and measurements are essential for making early predictions, which could be used to formulate guiding judgement. In addition, observational data complemented with advanced analytical tools can help to form basis for more realistic appraisal of potential problems and towards a more economic design of the excavation support system.

The customised earth retaining system used for the construction of the basement for the Esplanade – Theatres by the Bay differs from the conventional earth retaining system that is commonly used in deep excavation works. One of the governing factors is that the retaining system shall be a free-standing wall of about 11 metres high, that is constructed in soft marine clays of about twenty metres thick. In addition, the basement is located adjacent to an underground carpark building, vehicular bridge abutment and a 5-lane carriageway. It is pertinent that the extent of movements sustained by these nearby structures, due to the effects of the basement excavation works, are kept within allowable limits.

This paper presents the performance of a customised earth retaining system adopted for the deep excavation works. The lateral stability and rigidity of this unique excavation support system has been enhanced by arching action of the retaining system, which is mobilised through basement slabs cast along the perimeter of the semi-circular frame of the basement. Ground deformations and wall movements were closely controlled, and were successfully kept to a minimum with careful sequence of erection of the customised earth retaining system and excavation works.

The paper also discusses the field observations and monitored movements of the ground and the retaining system during the various stages of excavation works. Measured movements were also compared to those results obtained from finite element analyses.

2 SITE CONDITIONS

The Esplanade-Theatres by the Bay is located at Raffles Avenue, along the sea front of the Central Area of Singapore. The centre occupies an approximate area of 2.0 hectares. The existing ground level varied between RL 102.5m and RL 103.5m. The site is situated on reclaimed land, which is about 5 to 10 metres thick. The reclaimed fill consists generally of gravelly sand to silty/clayey sand and is brownish or yellowish grey in colour. It sometimes contains fragmented sea shells.

The site is geologically located in the Kallang Formation consisting of soils with marine and estuarine origin which forms a soft clay blanket over previous valley where the present site is situated. The marine clay is the predominant layer within this formation found at the site. Its maximum thickness encountered in the site investigation is about 20 metres. Organic clay layer, clayey sand and silty clay are encountered in only a few boreholes and they are discontinuous over the site.

Underlying the Kallang Formation is the Old Alluvium Formation, which consists of brownish grey and grey colour clayey silt, and cemented silty sand. The soils exhibited low permeability and the various degree of cementation usually disintegrates after a few days upon exposure. Although the upper portions are generally weathered, the Old Alluvium often provides bearing stratum with soils of Standard Penetration (SPT) values in excess of 50 which increases rapidly with depth.

The ground water level was high, about 2 metres below the existing ground level. Table 1 presents a summary of the soil parameters of the ground at the site.

3 SITE LAYOUT AND CONFIGURATION

Figure 1 shows the site layout and architectural configuration. A busy 5-lane carriageway is running along the northern edge of the Esplanade. The western side is connected to a two-level underground carpark of 11 m deep that was still under construction but at an advanced stage when the Esplanade was constructed. A dual 4-lane carriageway was sitting on top of part of the car park at the extreme eastern end. The car park is planned to serve primarily the users and audiences of the Esplanade. To the south is a vehicular bridge abutment which forms part of the above carriageway

Table 1. Values of soil parameters.

Type of Materials	γ (kN/m^3)	E (kN/m^2)	S_u (kN/m^2)	ϕ'	K_o
Fill	18	12,000	40	28°	0.5
Marine Clay	16	4,000	20	25°	0.7
Beach Sand	18	10,000	0	30°	0.5
Estuarine Clay	14	4,000	10	-	0.8
Old Alluvium (Completely Weathered)	20	100,000	100 to 200	35°	0.9

and is only less than 30 metres away from the nearest end of the Esplanade. The underground car park was constructed using top down construction method with diaphragm walls installed on all its perimeters except the side interfacing with the Esplanade due to the many necessary openings for connection between the car park and the Esplanade. The eastern side is reserved for future expansion of the Esplanade.

The Esplanade is roughly semi-circular in shape with an overall area of approximately 2.0 hectares. Figure 1 also shows the dimensions in plan and the architectural layout of the two important buildings to be housed within the Esplanade. The two buildings within are the Concert Hall and the Lyric Theatre, occupying the southern and northern halves respectively. Both buildings are of about equal size but slightly different shape.

Because of the extremely stringent acoustical requirements, the two buildings were not allowed any structural continuity or connections around them so as to isolate them from all possible external vibrations. They are basically supported on large numbers of specially designed and manufactured steel-laminated rubber-pad bearings at the base and at the four sides, a minimum of 50mm gap must be maintained throughout except at the lower wall area where a few spots were restrained laterally by special rubber-pads. As there is no continuous slab spanning across the entire floor area, the 11 metres high permanent basement wall was supported by a series of buttresses of one metre thick and six metres wide. The buttress walls are spaced at a distance of about 8 to 10 metres and are connected by one continuous waler-beam running at mid height of the wall. Each of the buttress walls was supported on two pile-groups below the foundation.

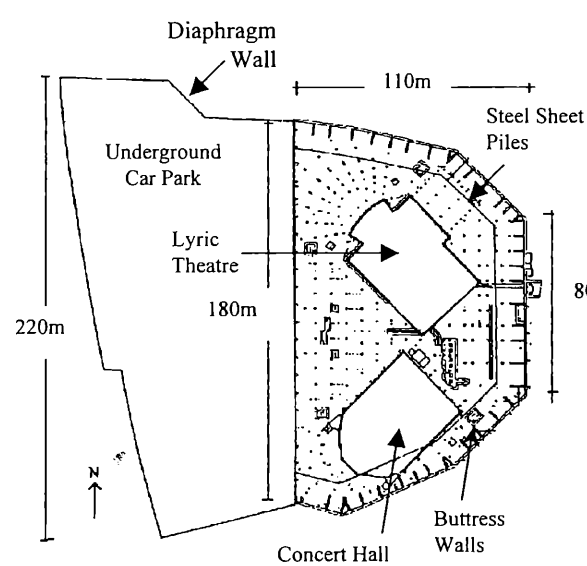

Figure 1. Site layout and configuration.

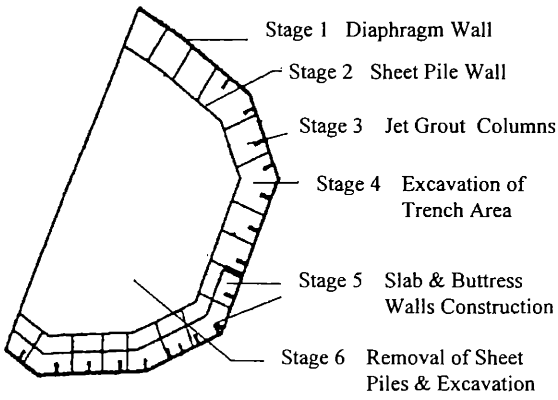

Figure 2. Construction and excavation sequence.

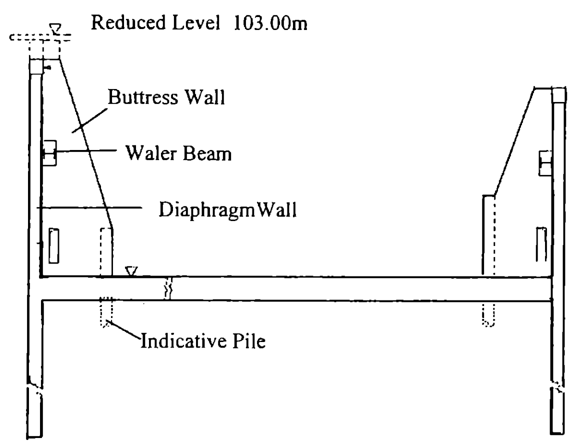

Figure 3. Typical section view of buttress walls.

4 CONSTRUCTION SEQUENCE

Figure 2 shows the construction and excavation sequence of works in relation to the basement and the adjacent underground car park structure for the various stages.

At the time when the Esplanade was constructed, all the diaphragm walls and the bottom basement slab of the adjacent carpark had been completed. This was an important consideration in the choice of design and construction sequence for the Esplanade. Figure 3 shows the typical cross section view of the buttress walls in relation to the diaphragm wall.

Due to the sheer size of the basement, traditional excavation method of strutting and cross bracing using long and large sections of steel members was deemed impractical and ineffective in restraining ground movement. The problem was further complicated by the stringent acoustical requirements mentioned above and therefore no continuous slab or beams could be constructed across to act as lateral supports. Ground anchor system was considered initially as an viable option, but was ruled out subsequently because of the high construction cost involved and the possibility of tendon strands being left in the ground which would affect the future development on the eastern portion of the site.

Diaphragm walls of one meter thick were first constructed from the existing ground level. Stability consideration dictated the need for the diaphragm wall to gain sufficient toe support in good bearing strata below the marine clay layer. The wall was embedded to about 4 to 6 metres deep into the Old Alluvium Formation. This was also to serve as an effective cut-off to the groundwater flow below the wall and thereby minimising the possibility of consolidation settlements during construction.

Steel sheet piles of FSP III type were simultaneously installed at a clear spacing of 18 metres along the diaphragm wall. The steel sheet piles were driven into 18 to 20 metres below ground level. The space between the sheet pile and the perimeter diaphragm wall effectively formed a semi-circular trench after the soils within it had been removed by traditional braced method. The width of 18 metres was chosen to allow sufficient working space for the construction of bottom slab and buttress walls. The foundation cast-in-situ bored piles for supporting the direct loadings of the buildings were constructed at the same time within the perimeter wall.

Prior to the commencement of excavation of the trench, jet grout columns were installed within the trench area at depths of between 11 metres and 13 metres below ground level. Design analysis showed that the highest bending moment and maximum bending could occur at this depth of the diaphragm wall. The jet grout columns was to improve and strengthen the soft clay layer at these depths level in order to form a virtual 'strut' just below the bottom slab to reduce the ground movement. Jet grout columns were installed using the triple tube machines, which enabled pre-cutting into the soil using water before ejecting cement grout at high pressures. This enables the reduction of uncontrolled heave and movement usually associated with grouting works. Installation of foundation bored piles within the trench area for supporting the buttress walls was followed but the piles were only cast up to the lowest slab level.

Excavation of the trench was carried out in three stages supported by two levels of steel struts at 1 and 5 metres below ground level respectively. This was followed quickly by the construction of slabs and buttress walls within the trench area. Steel struts were removed subsequently after completion of all buttress walls. The completed slab and buttress walls formed an arch and provided sufficient support for the free standing perimeter walls by acting against the completed bottom slab of the adjacent car-park. The rest of the excavation works within the Esplanade was completed easily when the steel sheet piles were extracted after the excavation was carried out using long-arm excavators positioned on the elevated platforms.

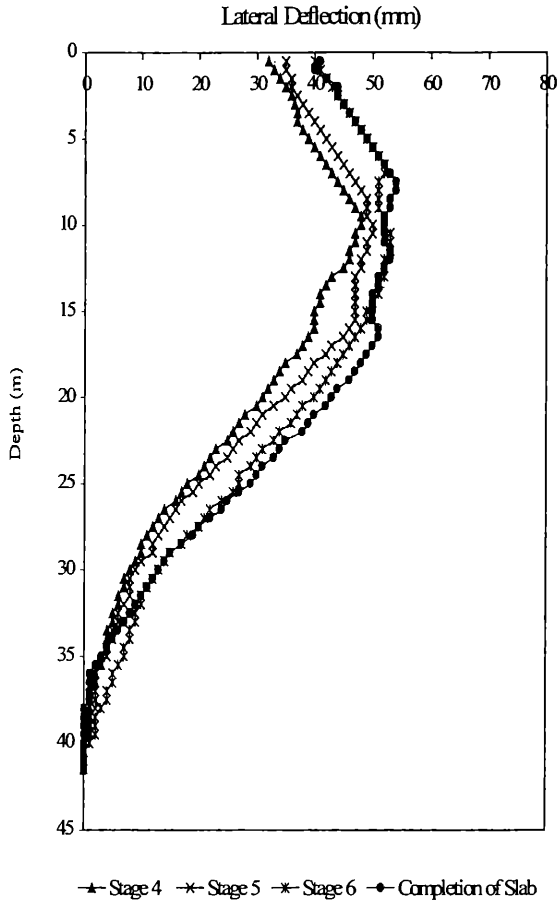

Figure 4. Measured lateral wall displacement.

This method of using the customised earth retaining system had enabled several activities to be carried out concurrently for a large site area. It was not only economical for construction, but also provided the necessary support against ground movement during the excavation works.

5 MONITORED RESULTS

A ground monitoring programme was implemented during the excavation of the basement work to monitor the behaviour of the braced excavation system. The focus of this paper is, however, limited to the monitored deflection of the diaphragm wall, which was measured by using inclinometers embedded in the wall. The depth of the inclinometer was installed to the toe level of the diaphragm wall.

During the stage involving the trench excavation, which is about 11m below the ground level, the maximum measured wall deflection is about 48mm, which occurred at 6m above the final excavation depth. The corresponding maximum surface settlement behind the diaphragm wall is in the order of 20mm to 30mm. The typical profile of the wall deflections within the trench excavation stage until the completion of basement slab has been plotted and shown in Figure 4. Initially, the deflection mode of the wall took the form of a cantilever that is oriented towards the excavation. Upon strutting, the upper portion of the wall movement was restrained and the lower third of the wall has developed into a bulging shape at the jet-grouted stratum. Similar deflection profile associated with the excavation was observed in other sections of diaphragm wall. It was also observed that the deflection profile decreased below the grouted layer. When the excavation within the two walls has completed, it was observed that the lateral wall movement continued at a much slower rate.

The summary of maximum measured wall movement with respect to the depths of excavation and stages of excavation is tabulated in Table 2.

At the final stage of the excavation works, as well as the completion of the bottom slab of the Esplanade and the erection of the buttress walls, the maximum measured wall deflection is only about 50mm. This is essentially about the same magnitude of wall deflection as compared to the earlier stage of work, when the excavation reached the formation level. The maximum ground settlement is about 40mm, which occurred at a distance of about 10m behind the diaphragm wall.

It is interesting to note that most of the wall deflections and ground deformations occurred during the trench excavation works, and subsequently it stabilised upon the full installation of the customised earth retaining system.

6 NUMERICAL MODELLING

The excavation works were back-analysed using a finite element program. Figure 5 shows a close-up view of a larger finite element mesh used in the analyses. The soil strata, as well as the grouted soil layer and buttress wall, were represented by six-noded triangle elements, while beam elements were used for the diaphragm wall, bottom slab, foundation piles and sheet pile wall. Interface

Table 2. Measured lateral movement of wall.

Stage of Excavation	Depth of Excavation (m)	Maximum Measured Lateral Movement (mm)
Excavate to 1st Strut Level	2	20
Excavate to 2nd Strut Level	6	37
Excavate to Formation level	11	48

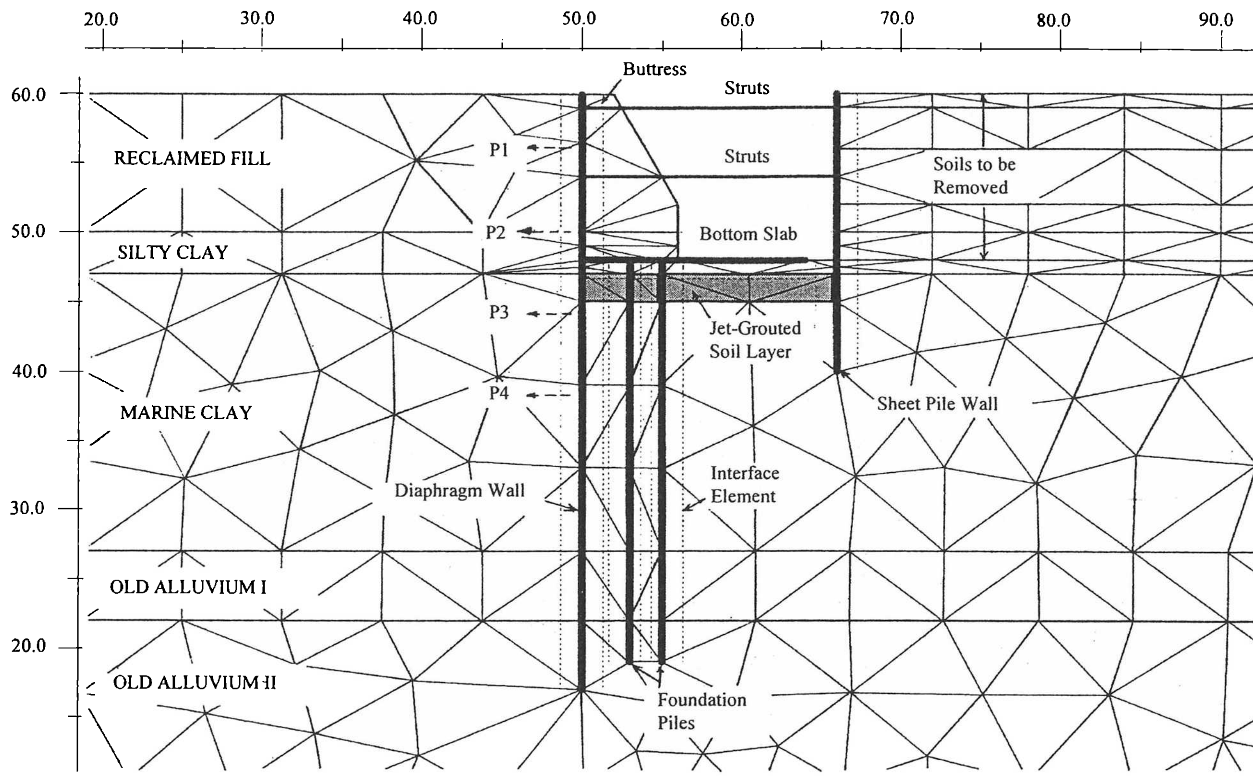

Figure 5. Close-up view of finite element mesh (Refer to Stage 5 of Figure 2).

elements were used to model the soil-structure interaction effects between the beam elements and adjacent soils. Figure 5 also shows the generalised soil conditions used in the analyses, basing on the Mohr-Coulomb model.

By using the sequential excavation and erection of buttress wall and bottom slab in accordance with the construction sequence shown in Figures 2 and 3, multiple stages of soil excavation and construction were modelled in the undrained analyses. The arching action of the retaining system, mobilised through the bottom slab and diaphragm walls that was constructed along the perimeter of the semi-circular frame of the basement, was not modelled initially in the back analyses as it is three-dimensional in nature involving complex interaction between the ground and the customised earth retaining support system. The analyses were carried out for the mid-section of the excavation works, where plane strain conditions have been assumed.

The computed ground displacement behind the diaphragm wall, due to the excavation works, was about 700mm. The lateral movement of soils developed into a typical cantilever mode of the diaphragm wall at the middle to upper third of the soil stratum, as depicted in Figure 6. The computed maximum wall deflection was about 950mm. This computed value was much higher than the measured deflection of the diaphragm wall of between 40mm and 60mm.

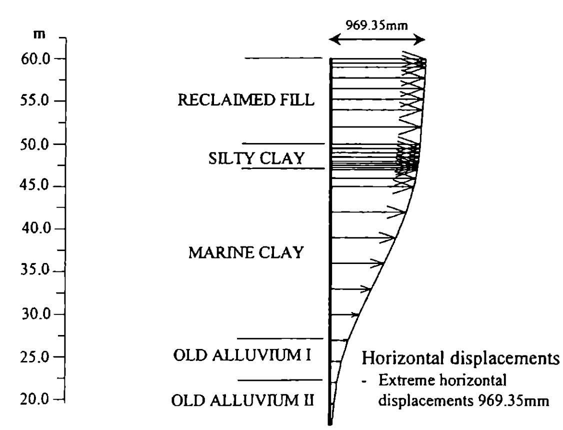

Figure 6. Computed deformation profile of diaphragm wall.

The large difference between the computed and measured wall deflection values could only be attributed to the successful application of the customised earth retaining system. The arching action of the retaining system, that was mobilised through the bottom slab and diaphragm walls constructed along the perimeter of the semi-circular frame of the basement, is believed to have provided the necessary additional support against substantial wall movement and ground deformation. In the design of the customised earth retaining system, the overall rigidity of the retaining system had incorporated the contributory effects of the arching action. Due to limited space of the paper, the details of the design would not be elaborated here. Instead, the significance of the arching action shall be simply illustrated with a parametric study that is presented in the following paragraphs.

The parametric study that was conducted for analysing the performance of the arching action of the customised earth retaining system for the excavation works, was carried out in 2-D plane strain condition. In the analyses, the arching action was assumed to provide a certain degree of active lateral restraint forces against soil pressures. These lateral forces were hypothetically represented by a series of anchors with varying amount of pre-stressing forces. The computed wall deflection profile was then curve-fitted to the measured wall deflection values. Through an iterative process, it was found that the anchors (P1 to P4 indicated in Figure 5) required pre-stressing forces of 100kN/m, 300kN/m, 500kN/m, and 800kN/m, respectively in order to achieve a similar order of magnitude of wall deflections as compared to the measured values. The corresponding ground subsidence obtained from the analyses was about 45mm, which is also comparable to the measured values. These low values of wall deflections and ground deformations indicate the successful enhancement of the load transfer mechanism, via arching action, to the supports of the earth retaining system.

It is understandable that the simulation of the above analyses for the parametric study may not be entirely correct, as it is not realistic to model the arching action with active lateral restraint forces. This is because the arching action is really a series of passive reaction in nature, and the mobilisation of the arching action is largely perceived to be stress and strain dependent. As 3-D numerical modelling is still a daunting challenge, it was then necessary to assume the arching action as a series of active lateral restraint forces based on the current state of the finite element method for 2-D analyses. Though the parametric study may not be modelling the problem accurately, however, it has met the objective of providing a simple illustration for showing the contribution of the arching action of the customised earth retaining system in minimising wall movement and ground deformation. In future with the advent of the advanced computing and information technology, three-dimensional numerical analysis will be a further option to conduct the assessment of such geotechnical engineering problems.

Up to this time, no site measurements were made to fully assess the arching action of the customised earth retaining system. Hence, the full merits of the arching action are still relatively unknown. The intensity of the arching action deserves preference, and as a further work it may be necessary to investigate experimentally the arching mechanism of the customised earth retaining system and to evaluate again the results with the basic assumptions of theories involved

7 CONCLUSION

The deep excavation for the basement of the Esplanade - Theatres by the Bay, Singapore, which adopted a customised earth retaining system, was successfully completed in very thick soft soil layers. Using the partially completed bottom slab and the buttress walls as supports, construction work could proceed smoothly for the majority of the site area thus was considerably more cost effective. Furthermore, the arching action of the customised earth retaining system could reduce effectively the ground deformations.

8 ACKNOWLEDGEMENT

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