Effect of Equivalent Wall Permeability on Groundwater Table in a Deep Excavation Project

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ABSTRACT: This paper presents the groundwater back-analysis of a deep excavation project. The project consists of a cut-and-cover tunnel and a main basement. The 700mm-diameter contiguous bored pile (CBP) retaining wall for the cut-and-cover tunnel is considered as 'permeable' due to the absence of cement grout columns behind the wall and thus is modelled with an equivalent permeability in finite element analysis. The results show an agreement with field measured standpipe data. The main basement section was modelled as impermeable wall as cement grout columns were present between successive CBPs. However, site observations show that installation of ground anchors had punctured the water tightness of the main basement CBP wall, thus causing the groundwater to seep out from the pre-bored holes meant for anchor installation. Therefore, the equivalent permeability from the cut-and-cover tunnel section was applied to the location of ground anchors to simulate the 'puncturing' of the CBP wall by ground anchor installation. Results from previous research were used to compare the groundwater drawdown.

KEYWORDS: deep excavation, back-analysis, groundwater table lowering, wall permeability, contiguous bored pile

1. INTRODUCTION

Kuching City in Malaysia is a rapidly developing city and has seen the need for more deep excavation constructions. A deep excavation project comprising a 150m long sloping cut-and-cover tunnel and a main basement excavation situated in the heart of the city is studied in detail. Century-old colonial-era buildings surround the project site with the distance of the closest building to the centre of the CBP wall is less than 2m. The site layout is shown in Figure 1. The cut-and-cover tunnel is used for an exit ramp connecting the main basement and a main road, thus having a varying depth from 7m deep to ground level. The retaining wall system consisted of 700mm-diameter contiguous bored pile (CBP) with centre-to-centre spacing of 750mm and horizontal struts. This section of the cut-and-cover tunnel could be considered 'permeable' due to the absence of cement grout columns that are supposed to plug the gaps between each successive CBP. Four water standpipes are available along the cut-and-cover tunnel, but only two will be discussed in this paper. A river is situated approximately 50m away from the end of the tunnel.

The main basement was constructed with the same CBP wall type but 200mm-diameter cement grout columns were present in between successive CBPs. Two levels of temporary ground anchors installed at a horizontal spacing of 2.25m and corner struts were part of the strutting system. However, no water standpipe was available in this area. The excavation depth at the main basement averaged about 10m from the existing ground level. The excavations and construction of substructures were carried out from the North East area in a clockwise direction.

Many of the existing shophouses and buildings were built in the early to mid-20th century. These shophouses are suspected to be constructed on timber bakau piles, estimated to be about 6-9m in length (Chong & Ong, 2014). Therefore, the shophouses are considered to be supported on these "floating" timber bakau piles and thus groundwater drawdown may easily induce settlements at these locations.

One of the concerns of deep excavation project is avoiding excessive ground movement which in part is contributed by the lowering of groundwater table. Clough and O' Rourke (1990) described the potential water flow that may lead to ground settlement, among them are flow through wall flaw and flow beneath wall toe. However, Kempfert and Gebreselassie (1999) reported that anchor installation activity contributed to large settlement due to drilling and fresh cement-bentonite slurry that was left to harden in the drill hole. Neither of these effects is included in the back analysis.

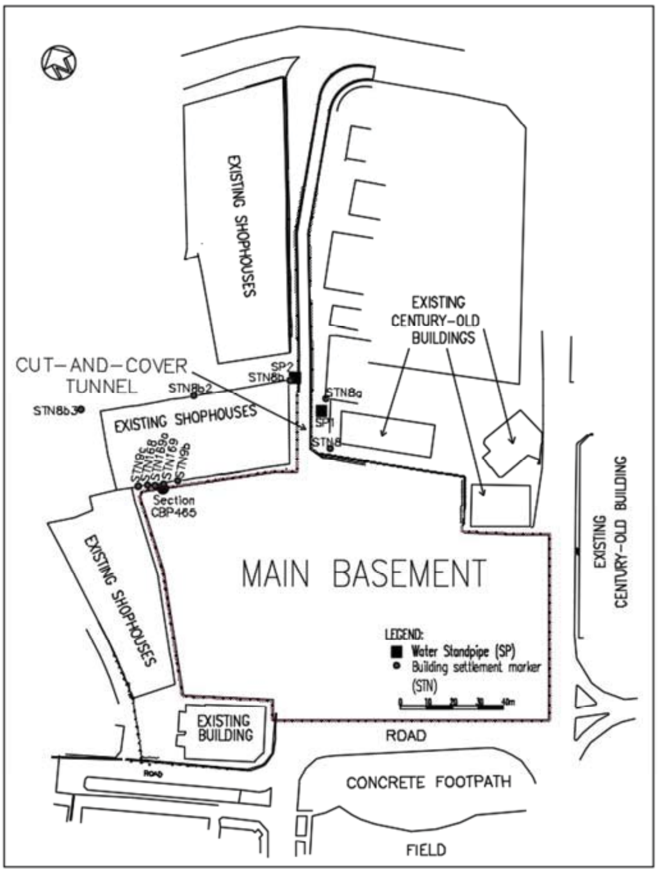

Figure 1 Site layout plan and locations of the cut-and-cover tunnel and main basement and the selected sections

This paper presents the use of an equivalent permeability in 2-D finite element analysis to represent the permeable CBP wall without cement grout column at the cut-and-cover tunnel for two sections, SP1 and SP2. Geostudio SEEP/W finite element analysis package was used in the back-analysis of the groundwater levels (GWL). The numerical results were then compared against readings obtained from the installed water standpipes for further verification. Subsequently, based on this understanding and concept developed, the equivalent wall parameters were applied to another wall section, CBP465 in the adjacent main basement area, where the installed cement grout columns (for water-tightness) behind the CBP wall had been punctured during the installation of 2-levels of ground anchors, thus rendering the main basement wall as permeable, similar to wall at the cut-and-cover tunnel area.

2. SITE CONDITIONS

2.1 Soil Conditions

Site investigations carried out indicated that soil materials are mainly loose sand and firm clayey silt with pockets of clay and peat. These layers have relatively low standard penetration test (SPT) 'N' values, approximately about 1-15 for the top 5m, followed by 15<N<50 in the next 5-7m or 8m from existing ground level. Rock formation of predominantly metamorphic phyllite can be found at the depth of about 6-8m below the existing ground level. Therefore, the CBP walls are socketed into phyllite. The soil profiles for the cut-and-cover tunnel and main basement are shown in Figure 2 and Figure 3, respectively.

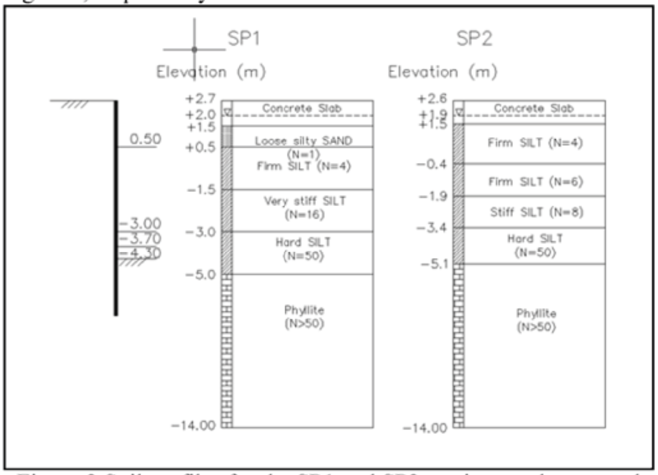

Figure 2 Soil profiles for the SP1 and SP2 sections at the cut-and-cover tunnel

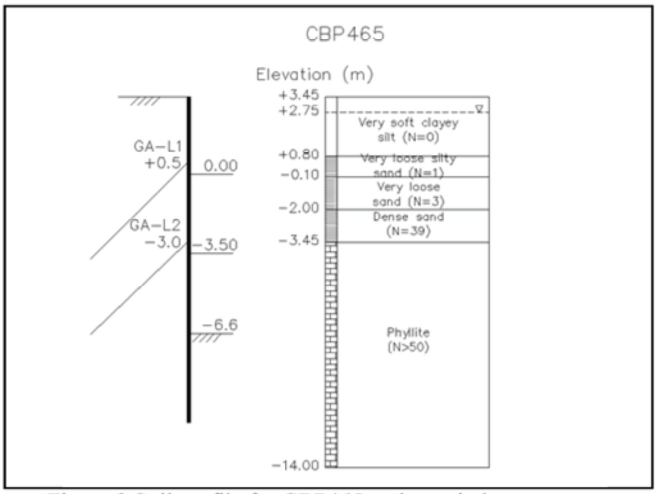

Figure 3 Soil profile for CBP465 at the main basement area

2.2 Construction Sequence

The project employed a bottom-up excavation method for both the unsupported cut-and-cover tunnel as well as the main basement supported by ground anchors. This provided the excavated site with a clear working space for the construction of the substructure elements.

2.2.1 Construction Sequence at Cut-and-Cover Tunnel

After the installation of the CBP walls, the bored piles were hacked to elevation RL+1.5m to enable the roof of the tunnel to be joined with the walls at a later stage. Then excavation proceeded to the required formation level while temporary strutting was provided at RL+1.5m.
Table 1 shows the construction sequence of the excavation and the duration for cut-and-cover tunnel.

2.2.1 Construction Sequence at Main Basement

Hacking of the pile heads was carried out to enable capping beam to be constructed at the existing ground level. Excavations were then carried out in stages to 0.5m below the ground anchor levels and ground anchors were installed in between excavation steps. Three excavation stages were carried out and two layers of ground anchors were installed and pre-stressed. Table 2 shows the construction sequence of the excavation and the duration for main basement.

Table 1 Construction sequence for cut-and-cover tunnel

Stage	Construction Activity	Duration (Days)		Cum. Duration (Days)	
		SP1	SP2	SP1	SP2
1	Excavation 1 to RL+0.5m	1	3	1	3
2	Excavation 2 to RL-3.0m	3	9	4	12
3	Excavation 3 to RL-3.7m	4	-	8	-
4	Excavation 4 to RL-4.3m	5	-	13	-
5	Excavation remained at final level	56	56	69	68
6	Construction of skinwall	7	7	76	75
7	Monitoring continued after the construction of skinwall	181	78	257	153

Table 2 Construction sequence for main basement

Stage	Construction Activity for CBP465	Duration (Days)	Cum. Duration Starting at Day 251 (Days)
1	Installation of CBP Wall	50	301
2	Excavate to 0.5m below the first level of ground anchor	6	307
3	Install and stress the first level of ground anchor (GA-L1) (RL+0.5m)	30	337
4	Excavate to 0.5m below the second level of ground anchor	27	364
5	Install and stress the second level of ground anchor (GA-L2) (RL-3.0m)	12	377
6	Excavate to the formation level (B3) (RL-6.6m)	10	387

3. SITE OBSERVATIONS AT MAIN BASEMENT

As pointed out earlier, the CBP wall is socketed into metamorphic phyllite, which is generally erratic upon extraction from the ground due to relatively intense foliation and fissures as evidenced by presence of slickensides (smoothened and shiny surfaces at joints due to metamorphism), but as an in-situ rock mass it can be tightly-jointed (Ong, 2012). Cement grout columns that were installed in between successive piles until the depth where phyllite was found, was effectively assumed as an impermeable wall. Thus, bounded by the phyllite and the CBP wall, a water-tight area behind the wall was created. Groundwater table was generally found to be about 0.7-1.0m below the ground level.

Rotary wash drilling method was used to install the ground anchors and soil particles have been observed to have washed out from the holes. As the design calls for ground anchors to be installed at 2.25m c/c spacing coinciding with the positions of the grout columns, this effectively 'punctures' the water-tightness of the CBP wall. Even though each hole was grouted immediately after the insertion of ground anchor, curing will take time before the grouted hole can provide an effective seal.

For this wall section, site observation indicated that at first opportunity when the puncture occurred, the ground water showed immediate response by seeping through the drilled holes, thus the start of ground water losses. Where loose sand layers and peat pockets were present, ground water losses could be substantial.

Figure 4 shows the photo of a section that had been excavated to the final level. Water stain marks were clearly observed at all the ground anchor positions at both ground anchor levels. At the corner (right side of the photo) where corner struts were used, dry bored piles could be seen, indicating no water loss through the wall. This suggests groundwater was seeping out from the location of the ground anchors due to the presence of drilling-induced cracks in the grout columns. However, no groundwater reading was available at this section.

Relatively large building and ground settlements with small horizontal wall deflections were observed at these sections. This observation will be discussed in a later section, together with the back-analysis results. Adjacent structures may experience damage from excessive settlements. Deep excavation works lower the groundwater table and often induced settlements to buildings and ground adjacent to it. Pickles, Lee, and Norcliffe (2003) reported that when a cut-off wall was used, the drop in groundwater level is significantly reduced. Thus, it is logical to assume that the CBP wall acts as a cut-off, but due to the puncturing of ground anchors, the wall is no longer water-tight. As described by Clough and O' Rourke (1990), settlement will occur if groundwater table is lowered and the lowering of groundwater table can be attributed to a few factors, among it a flaw in the wall. In this site, the flaw is the puncturing of the CBP wall with ground anchors.

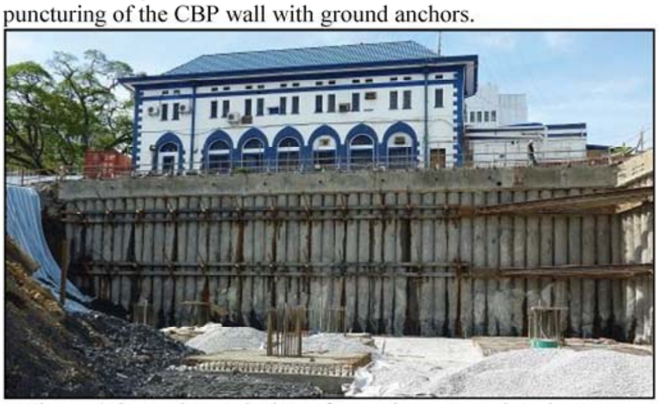

Figure 4 Groundwater leakage from where ground anchors were installed (Chong & Ong, 2014)

4. FINITE ELEMENT MODELLING

Geostudio SEEP/W 2007 Version 7.23 package was used in the back-analyses. An initial steady-state analysis was performed to determine the phreatic surface before the excavation process. Transient analysis was used to capture the time component in the analysis. "Saturated/Unsaturated" material model was selected for all the analyses.

The CBP wall was assumed to be "wished-in-place" after the initial in-situ condition was analysed. The effect of the construction of capping beam at the head of the CBP wall was not considered in this analysis. Constant "unit flux (q)" boundary condition was used to represent the equivalent wall permeability.

For the cut-and-cover tunnel, the cross sections of SP1 and SP2 was modelled as a 2-D plane strain analysis assuming that the excavation is at the same level throughout the wall length. In reality, this cut-and-cover tunnel is a ramp leading from RL-4.0m to the highest point at RL+3.6m. The pile length and embedment length varies along the tunnel. This information was not captured in a 2-D plane strain analysis whereas the excavation at main basement was considered a pure 2-dimnesional plane strain as the pile length, excavation depth and embedment length was consistent throughout the length of the wall. Table 3 lists the differences between the input parameters used in the back-analyses of the different sections.

Table 3 Input parameters in the back-analyses

Section	Pile Length (m)	Excavation Depth (m)	Slope	Embedment Length (m)
SP1	9.7	7.0	Yes	2.7
SP2	8.6	5.6	Yes	3.0
CBP465	15.1	10.0	No	5.1

4.1 Equivalent Permeability of Walls

The CBP wall was represented as an equivalent 2-D wall in the back-analysis. Due to this, only one permeability value is allowed to be input into the analysis. The concept of equivalent permeability is introduced to determine the permeability of the stratified soil layers and later on the permeability of the wall due to the 50mm gaps (represented by the equivalent permeability of soils) in between the bored piles (represented by permeability of concrete). The equivalent wall permeability was calculated using Eq. (1).

$$k_{eq} = \frac{k_1 H_1 + k_2 H_2 + \ldots + k_n H_n}{H_1 + H_2 + \ldots + H_n} \quad (1)$$

where $k_1, k_2, \ldots, k_n$ = permeability of soil for different layers; and $H_1, H_2, \ldots, H_n$ = thickness of soil for different layers. For tunnel sections, equivalent wall used was determined from Eq. (1) where k_1 = equivalent permeability of soil and k_2 = permeability of concrete.

4.2 Effect of particle size on soil permeability

The permeability of the soil is affected by many factors, among it the grain-size distribution, void ratio and degree of soil saturation (Das, 2008). The soils are modelled with appropriate permeability values. As standard penetration test SPT 'N' values are frequently used in gauging the characteristics of the soils, the permeability values for the soils are estimated based on the SPT 'N' values and unit weight obtained from soil investigation works. With lower SPT 'N' and unit weight, higher permeability value is used. The range of permeability values are given in Table 4.

Table 4 Permeability of soils

Material	Permeability (m/s)
Sand	10^{-5} to 10^{-6}
Silt	10^{-6} to 10^{-7}
Phyllite	1×10^{-10}
Concrete	1×10^{-12}
Soil layers	3×10^{-6} (equivalent)
Wall at cut-and cover tunnel	1×10^{-8} (equivalent)
Wall at main basement	1×10^{-8} (equivalent)

4.2 Results and Discussion

4.2.1 Cut-and-Cover Tunnel

Figure 5 shows a typical cross section of the result of the back-analysis. The groundwater level can be seen lowering down from the left edge of the cross section. Figure 6 and Figure 7 show reasonable match between the groundwater profiles measured at site and predicted from SEEP/W for SP1 and SP2 respectively. It is observed that during the excavation period that lasted about 12-13 days, the groundwater level is lowered at a very fast rate, similar to the rate of excavation. As the excavation depth of SP1 is deeper (RL-4.3m) compared to SP2 (RL-3.0m), the groundwater drawdown for SP1 is also lower (about RL-2.0m) as compared to SP2 (about RL-1.5m). Following the excavation to the final levels, there is a period of rest where the preparation for skinwall construction was carried out. It can be seen that the groundwater was at almost the same level but increasing slowly. This is most likely due to the recharge from a nearby river and precipitation but because the wall is still permeable, groundwater is still able to flow through the gaps in between the bored piles. Once the skinwall has been constructed, the groundwater level rises steadily throughout the remaining monitoring period. This also indicated that the skinwall is effective as a water cut-off wall. It is also noted that the effect of the level variation due to the ramp along the tunnel is ignored.

The building settlement markers nearby recorded a faster rate of settlement before the skinwall was constructed in both cases. After the construction of skinwall, it is observed that the settlement slowed down considerably. Settlement marker STN08a near to SP1 had shown some heave. This could be attributed to the sand layers at SP1 where it created a buoyancy effect in that the sand was fluctuating with the increase in groundwater table.

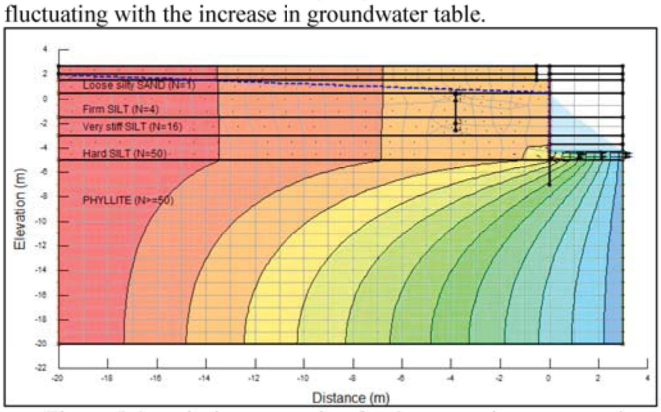

Figure 5 A typical cross section for the cut-and-cover tunnel

4.2.2 Main Basement

As discussed earlier, site observations indicated that the installation of ground anchors had actually 'punctured' the water tightness of the CBP wall as groundwater was observed to have seeped out through the ground anchor heads during and after construction. The CBP wall was modelled as a cut-off wall. However, the parameters and boundary conditions from the cut-and-cover tunnel were then applied to the location of ground anchors to simulate the seepage at these points. The concept of equivalent wall permeability was used to simulate this puncturing effect. At the anchor heads, groundwater is allowed to flow through the wall by applying a boundary condition to represent an equivalent permeability. A cross section of CBP465 at the final level of excavation showing the groundwater drawdown is presented in Figure 8.

The transient groundwater level was compared with previous results back-analysed with PLAXIS 2-D as reported by Chong and Ong (2014), in which the groundwater was deliberately drawndown and comparison of field measured and predicted settlement showed a reasonable agreement, as shown in Figure 9(a).

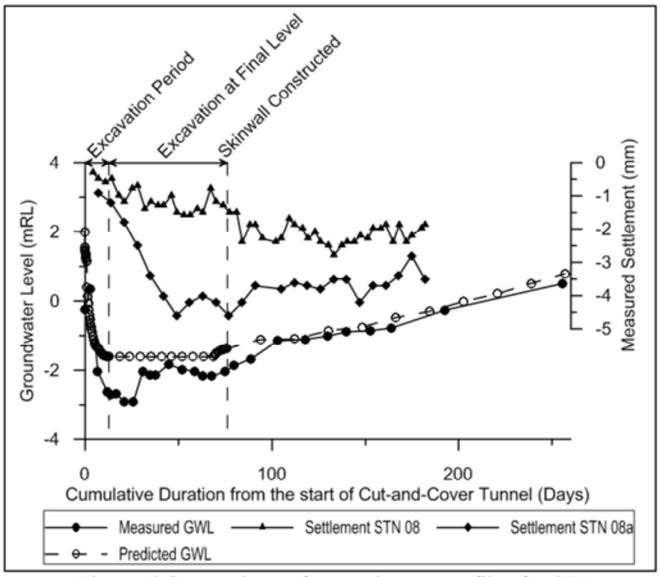

Figure 6 Comparison of groundwater profiles for SP1

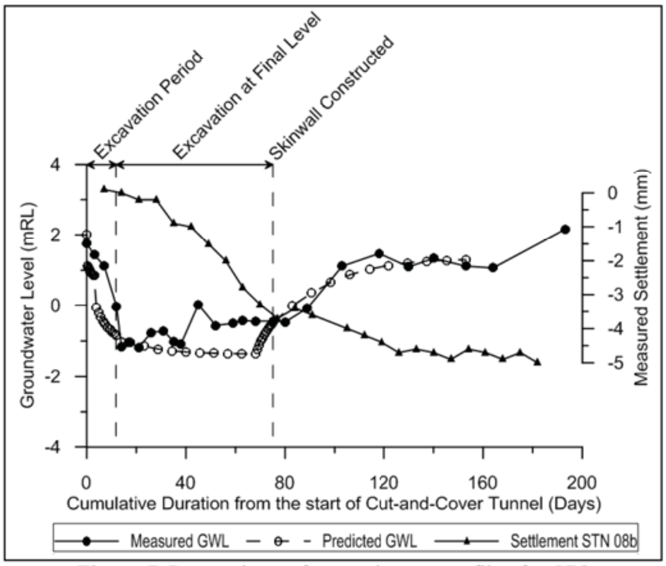

Figure 7 Comparison of groundwater profiles for SP2

Since the previous analysis was not time-dependent, the groundwater levels and predicted settlements were not plotted as continuous line, rather as discrete data points.

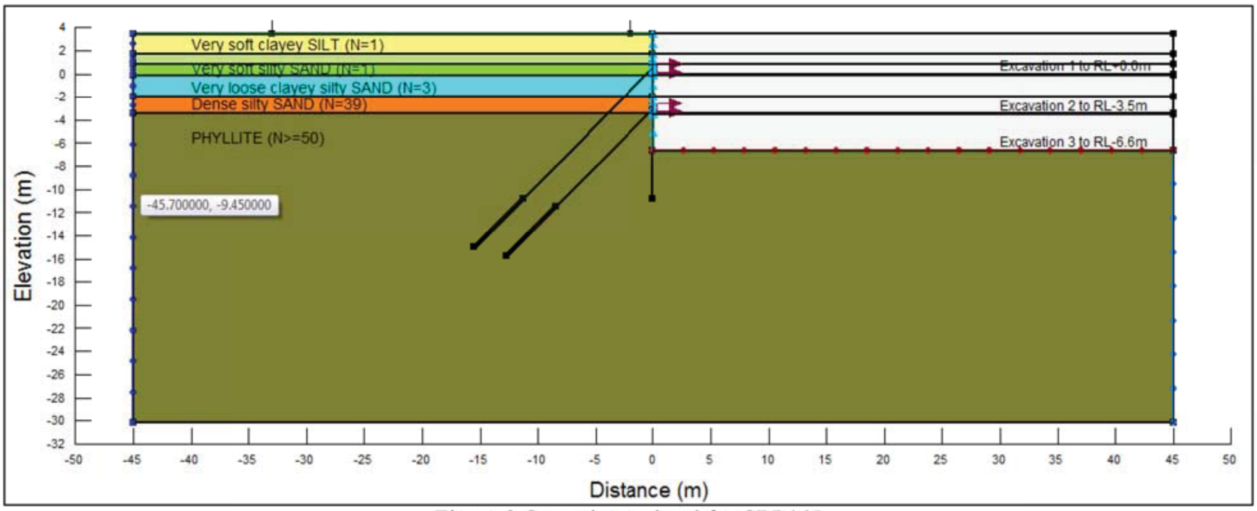

Figure 8 Groundwater level for CBP465

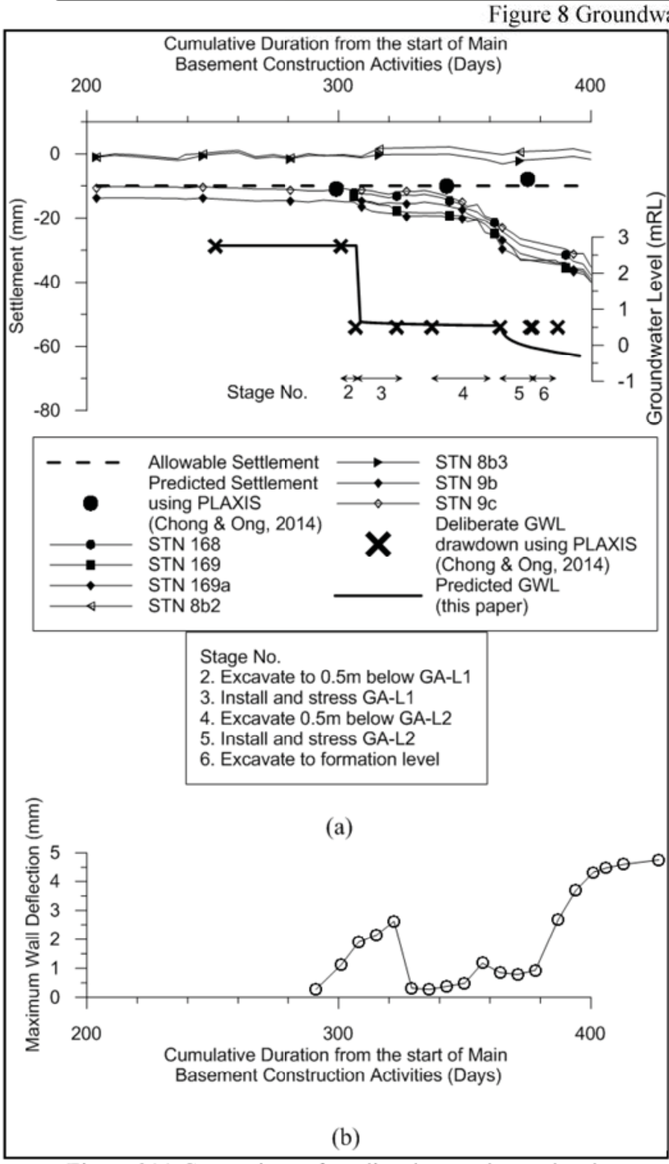

Figure 9(a) Comparison of predicted groundwater level benchmarked with settlements from previous research (b) maximum wall deflection corresponding to various construction activities and settlements

In this paper, the predicted groundwater level using SEEP/W is plotted as a continuous line to show the groundwater drawdown at the different stages of excavations and ground anchor installations. It can be seen that the groundwater level was maintained at RL+2.75m (initial GWL) during in-situ analysis and Stage 2. When ground anchors were installed, the groundwater level dropped to about RL+0.5m (2.25m depth), which is consistent with the deliberate water drawdown in the previous analysis. The groundwater continues to drop at a slow rate from Stage 2 to Stage 4. This is because at these stages, the ground anchors had 'punctured' the CBP wall and groundwater is seeping out from the first layer of ground anchors. When the second layer of ground anchors were installed at Stage 5, the groundwater level continue to drop further because the CBP wall now has two points (first and second layers of ground anchors) where the groundwater is able to seep out. The previous research concluded that the deliberate water drawdown to simulate the 'puncturing' effect was possible as the predicted settlements in the previous research were benchmarked with field measured settlements. Thus, when the predicted groundwater level from SEEP/W is compared to the deliberate groundwater drawdown level, it is deduced that the settlement is equivalent. Ultimately, the predicted settlement should be back-analysed with SIGMA/W and it is an on-going work.

In Figure 9(b), relatively small wall deflections are observed. The maximum wall deflection ($\delta_{h,max}$) is 5mm compared to 40mm maximum settlement ($\delta_{v,max}$). Generally, the relationship between maximum wall deformation and maximum ground surface settlement in similar soil condition is $\delta_{v,max}$ = (0.5~0.75) $\delta_{h,max}$ (Clough & O' Rourke, 1990; Hsieh & Ou, 1998). As the field observation shows an inverse relationship instead, therefore, it is obvious that groundwater loss is indeed the culprit that caused the relatively large settlements to occur.

5. CONCLUSION

This paper discusses the behaviour of groundwater table behind the retained wall in a deep excavation project. Two types of CBP wall conditions were highlighted, i.e. without and with cement grout columns between the successive bored piles, which renders permeable and impermeable walls respectively. In the case of the cut-and-cover tunnel, the groundwater table was lowered when permeable walls were installed at site. Equivalent wall permeability was used in the back-analyses to represent the permeable wall. Predicted groundwater responses show reasonable agreement with field measured groundwater table.

The parameters used in the cut-and-cover tunnel were extended to the main basement where field measurements of groundwater table are not available to predict the groundwater responses. Even though the wall is impermeable due to the presence of cement grout columns, groundwater was observed to seep out at the heads of ground anchors. Thus, the concept of equivalent wall permeability was applied to the location of ground anchors to predict the groundwater level. The results were compared to previous research where the predicted settlements with deliberate groundwater drawdown were benchmarked with field measured settlements. Both groundwater levels were similar, especially during the first ground anchor installation. However, the groundwater level continued to drop after the second ground anchor installation, as it effectively simulates the 'puncturing' of the CBP wall with ground anchors.

Future works of this project would include benchmarking the results of settlement and wall deflection profiles that are available at the main basement with the element of time.

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