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Study of a 15 m vertical soil nailed wall at Capella@Sentosa

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ABSTRACT: The Knolls at the Capella (a six star resort hotel) of Sentosa Island involved the construction of a vertical soil nail shotcrete retaining structure to support an open excavation of 15 m height, and to preserve the existing historic. The design follows the French code, Recommendation Clouterre 1990. During stage construction of soil nail walls, significant ground displacements were expected as soil nail is a passive soil reinforcement system. The ground displacements were predicted using FEM program Plaxis. Wall deflection and ground settlements were monitored and minimal damage were caused to Tanah Merah house throughout the process of soil nail wall construction. A parametric study has been carried out on important parameters inherent to the soil and soil nails. This study showed which parameters are significant in the design of such a retaining structure.

1 INTRODUCTION

Soil nailing is an in-situ ground reinforcing method for retaining excavations and stabilising slopes by passive inclusions. Soil nails are extremely effective in stabilising existing slopes or where slopes have to be steepened.

The six star hotel Capella@Sentosa is an example where a permanent vertical slope has been stabilised using soil nailing reinforcement. Various field instruments, including inclinometers, settlement markers and water stand pipes, have been placed on site as the near vertical slope is being constructed and measurements taken with progression of the excavation. The measurements included settlements of existing structures (Old Tanah Merah House) and lateral displacement of the cut slope from inclinometer readings, and ground water levels.

Predictions of the deformation behaviour of a soil nailed structure are required to ensure that displacement limits set by the authorities are not exceeded. The case at Sentosa provides opportunity to validate the use of a finite element analysis for a soil nailed problem. For closely spaced soil nails, equivalent 2D FEM models can give good results (Tan et al, 2005). Once the models are calibrated to fit the deformations obtained on site, a parametric study on was conducted to determine the sensitivity behavior of the soil nailed system. With the parametric study, engineers will be able to know which parameters are more critical in the design of soil nailed walls.

2 GEOLOGY AND SOIL PROFILE

The prevailing geological formations underlying the site are Rimau Facies and St. John Facies of Jurong Formation. The Geological Map is presented on Figure 1. Eight boreholes (Figure 2) revealed that the site is underlain by the Residual Soils of Jurong Formation. The subsurface strata of the site consist of weathered surficial fill, predominantly of yellowish brown silty sand. The density index of the fill is loose. This unit is approximately 1 m to 4 m thick, with an average thickness of 3 m. The fill is underlain by the Residual Soils of Jurong Formation which appeared in the form of silty sand. The relative densities of this unit were found to vary between loose to very dense and generally improving with depth. Table 1 showed the four idealized layers of soil according to SPT blow counts.

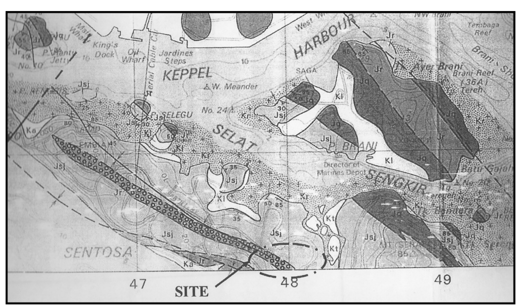

Figure 1. Geological map of site at Sentosa.

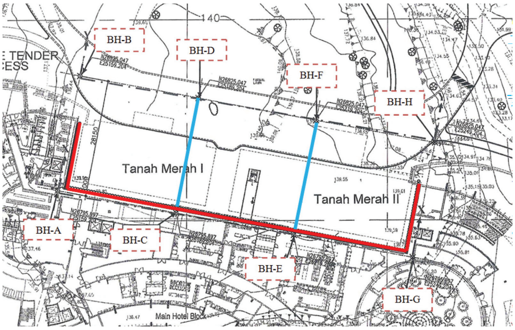

Figure 2. Borehole location.

Table 1. Soil layers found on site.

Layer	Identification	SPT N blows /30 cm
1	Loose silty sand [<10]	<10
2	Medium dense silty sand	10–40
3	Dense silty sand	40–100
4	Very dense silty sand	>100

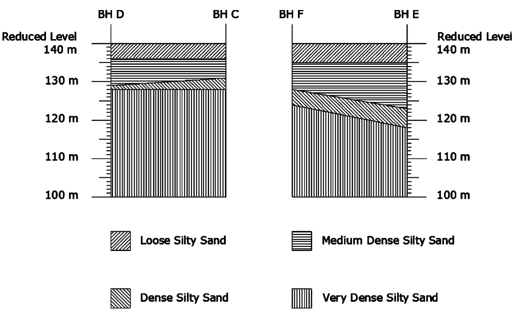

Figure 3. Soil profile.

Two sections have been chosen for the FEM study of the soil nailed wall behavior. These sections are CD and EF as shown in Figure 3.

3 INSTRUMENTATION RESULTS

Figure 4 showed the instruments installed on site.

3.1 *Inclinometer*

Unfortunately only one inclinometer is near the two analyzed sections, namely inclinometer I2 near borehole C and also the inclinometer was installed quite late, after some excavation had taken place. There were also other problems related to the readings. Figure 5 shows the readings retrieved as the excavation was being carried out. It shows the readings taken after the excavation reached a 5 m depth, a 10 m depth and finally a 15 m depth when the excavation was completed.

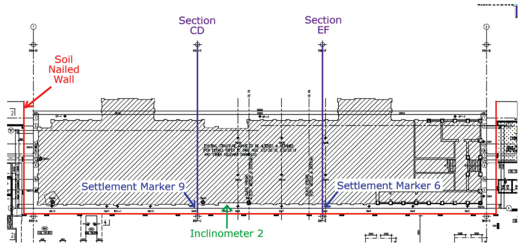

Figure 4. Instrument location.

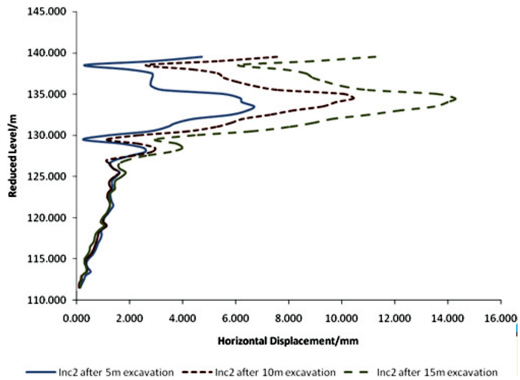

Figure 5. Inclinometer readings.

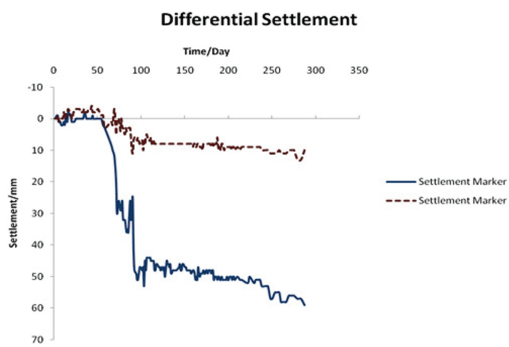

Figure 6. Settlement readings.

3.2 *Settlements*

Various settlement markers were placed around and inside the old Tanah Merah House. Settlement marker 6 was placed just behind borehole E and settlement marker 9 was placed behind borehole C. The readings from these two settlement markers are relevant to the 2 sections analyzed in this paper. Figure 6 showed the settlement readings and consequently the differential settlement induced between the two sections.

Table 2. Maximum settlement.

Settlement marker 9 [Behind BH-C] [mm]	Settlement marker 6 [Behind BH-E] [mm]
51	7

The maximum settlement registered by the settlement markers occurred after the full excavation for the wall was completed are summarized in Table 2.

3.3 *Water standpipe*

Figure 7 shows the water standpipe readings. The data showed that the ground water levels were below the base of the excavation (RL124 m) throughout construction. Being very stiff soils, a drained analysis is more appropriate for this site.

4 FEM MODELLING

A Mohr-Coulomb model was used for the stiff residual soils assuming drained behavior.

4.1 *Soil Mohr-Coulomb parameters*

From consolidated undrained triaxial compression test c' and ϕ' were determined for the residual layers. Based on other excavation experience in similar soils, it is estimated that a correlation of E = between 1 N and 2 N MPa would generally apply for these residual soils. All soil materials used have a Poisson's Ratio of 0.3 and a permeability of 0.01 m/day. A correlation of E = 1 N was used for the worst credible soil profile namely Section EF and a correlation of E = 2 N was used for Section CD to obtain reasonable values for the 2 models done in Plaxis. Both models were run in fully drained conditions. The parameters used are listed in Tables 3–5.

4.2 *Soil nail and shotcrete properties*

The soil nails and shotcrete were modeled using the equivalent thin plate theory. The EI and EA of the plate elements used in Plaxis are actually EI/S_h and EA/S_h, where S_h is the horizontal spacing of the nails. For the shotcrete, the equivalent EI and EA were calculated per metre run of wall. The equivalent of nail stiffness E is obtained from calibration to pullout tests results.

All the plate elements representing the nails and shotcrete were modeled as elastic materials with a Poisson's ratio of 0.1 and a weight of 1 kN/m^2. Listed below are the material properties for the plate elements used in the Plaxis model for both sections CD and EF.

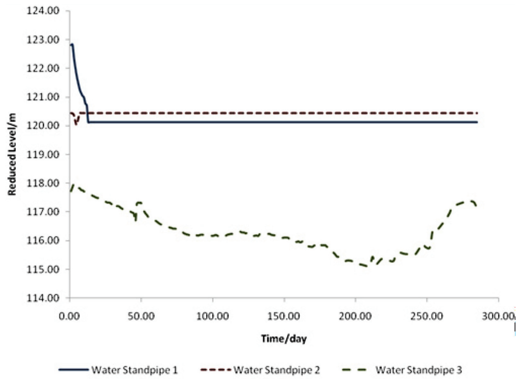

Figure 7. Water standpipe readings.

Table 3. Soil type legend.

Layer no.	Soil type
1	Loose silty sand
2	Medium sense silty sand
3	Dense silty sand
4	Very dense silty sand

Table 4. Soil properties section CD (E = 2N MPa).

No	γ_unsat kN/m^3	γ_sat kN/m^3	E_ref kN/m^2	c_ref kN/m^2	ϕ °	ψ °
1	18	20	10000	5	30	0
2	18	20	40000	10	32	2
3	18	20	120000	15	35	5
4	19	21	200000	20	40	10

Table 5. Soil Properties Section EF (E = 1N MPa).

No	γ_unsat kN/m^3	γ_sat kN/m^3	E_ref kN/m^2	c_ref kN/m^2	ϕ °	ψ °
1	18	20	5000	5	30	0
2	18	20	20000	10	32	2
3	18	20	60000	15	35	5
4	19	21	100000	20	40	10

5 FEM RESULTS

FEM study for sections CD and EF and parametric studies are presented below.

5.1 *Deflection of wall*

The results of wall deflection predictions at 5 m, 10 m and 15 m depths are shown in Figure 8.

Table 6. Plate element properties for soil nails and shotcrete.

Name	EA [kN/m]	EI [kNm^2/m]	M_p [kNm/m]	N_p [kN/m]
Shotcrete	5000000	16667	1.00E + 15	1.00E + 15
Soil nail type 1	169000	42200	1.00E + 15	1.00E + 15
Soil nail type 2	141000	35200	1.00E + 15	1.00E + 15
Soil nail type 3	141000	35200	1.00E + 15	1.00E + 15

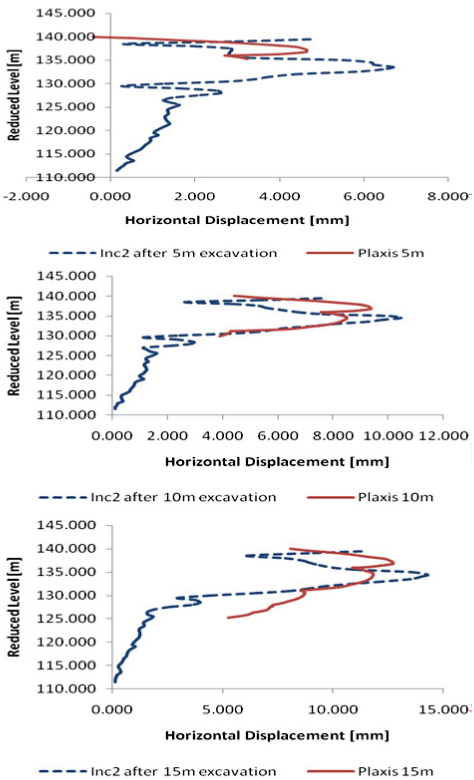

Figure 8. Wall deflections at 5 m, 10 m and 15 m depths.

The stiff soils combined with closely 1 m square grid spaced nails results in very small wall deflection of less than 0.1% of wall height, in this case.

5.2 *Ground settlements*

The predicted settlements under Tanah Merah house for sections CD and EF are shown in Figure 9.

These indicate that the maximum settlements of section CD would be about 15 mm, and the weaker

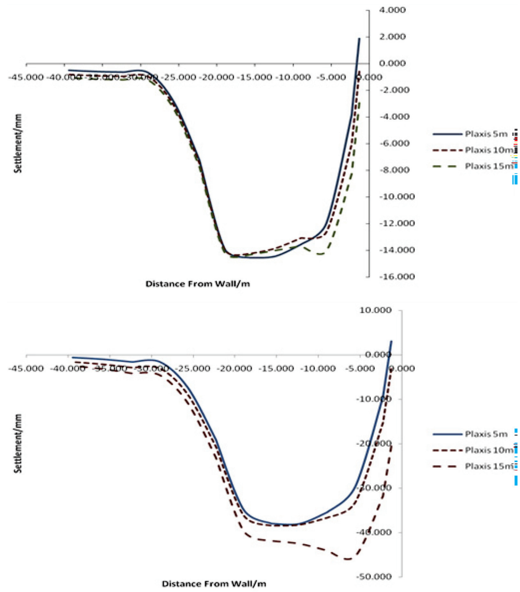

Figure 9. Predicted settlements of sections CD and EF.

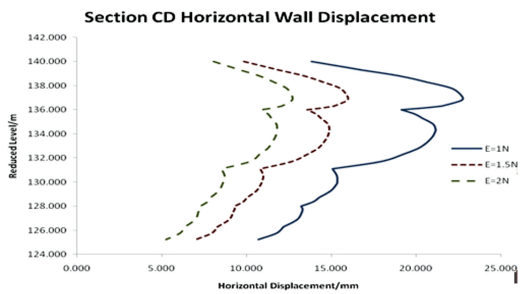

Figure 10. Influence of soil stiffness on deflections at CD.

section EF would be about 50 mm, consistent with the measurements in Figure 6.

5.3 *Parametric study*

The study was done to examine the influence of soil strength and stiffness, and nail axial and bending stiffness and lengths on the soil nailed wall.

Soil Stiffness was varied using different correlations between SPT N values and Young's Modulus of soil, E = 1 N, 1.5 N and 2 N MPa. Increased soil stiffness would reduce wall deflection near proportionately as these stiff soils remain essentially elastic when stiffen with closely spaced soil nails as in Figure 10.

Similarly, ground settlements are near proportionately reduced with increase of soil stiffness, as in Figure 11. However, the improved results from E = 1 N to 1.5 N is larger than from E = 1.5 N to 2 N.

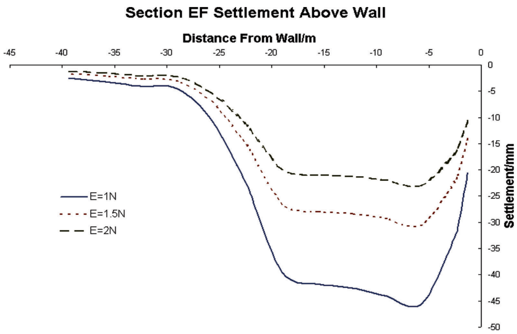

Figure 11. Influence of soil stiffness on settlements at EF.

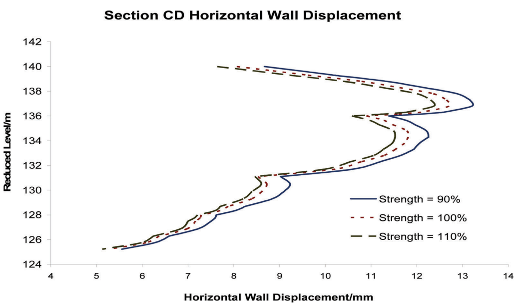

Figure 12. Influence of soil strength on deflections at CD.

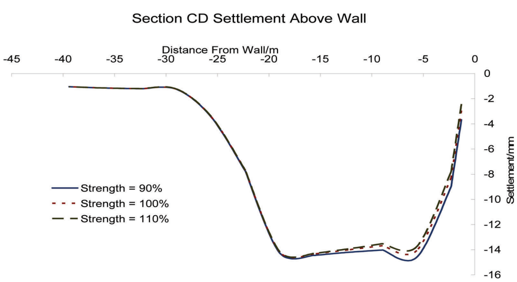

Figure 13. Influence of soil strength on settlements at EF.

Soil strength were varied by plus minus 10% from initial models. Three models were run with soil strengths of 90%, 100% and 110%. For the soil strength, c' and tan ϕ' were varied concurrently since the equation of shear strength is based on Mohr-Coulomb criteria as in Equation 1.

Figures 12 and 13 showed that soil strength is not sensitive as the soils response are essentially elastic with relatively small amount of soil yielding.

The nail bending stiffness of the soil nails were varied between 50% and 150% of the initial Plaxis models. Three models were run with nail stiffness of 50%, 100% and 150%. The results in Figures 14 and 15 showed that nail bending stiffness has little influence on wall deflections and ground settlements. This is consistent with Clouterre 91 that bending stiffness would contribute less than 15% to nail capacity.

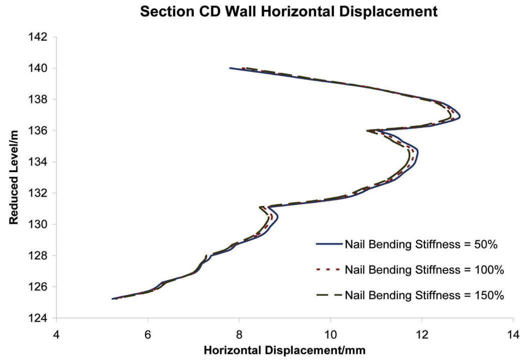

Figure 14. Influence of nail bending stiffness on deflections at CD.

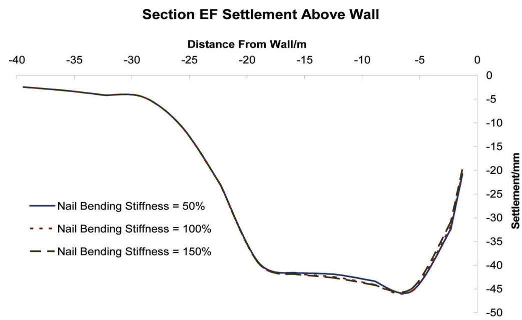

Figure 15. Influence of nail bending stiffness on settlements at EF.

The nail axial stiffness of the soil nails was varied between 50% and 150% of the initial Plaxis models. Three models were run with nail stiffness of 50%, 100% and 150%. The results in Figures 16 and 17 showed that nail axial stiffness has strong influence on wall deflections and little influence on ground settlements. This is consistent in that nail axial stiffness acts mainly in the horizontal direction restraining wall lateral movement but not ground vertical settlements.

The length of the soil nails was varied between 80% and 120% of the initial Plaxis models. Three models were run with nail stiffness of 80%, 100% and 120%. The results in Figures 18 and 19 showed that length of nails had greater influence on wall deflection and little effects on ground settlements.

6 CONCLUSIONS

It can be seen that the soil stiffness and the axial stiffness of the soil nail are quite important in the design of such earth retaining structures in stiff soils.

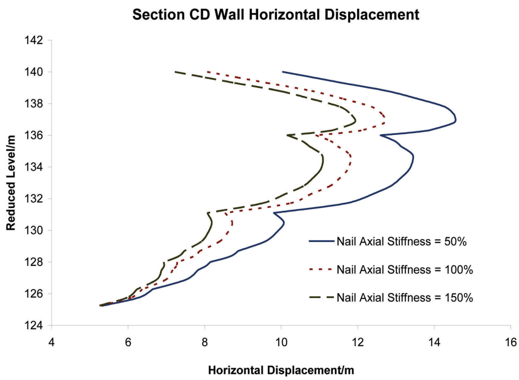

Figure 16. Influence of nail axial stiffness on deflections at CD.

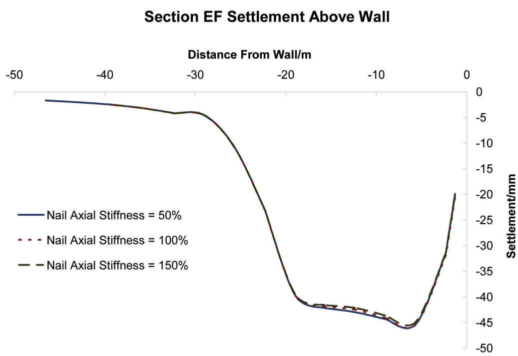

Figure 17. Influence of nail axial stiffness on settlements at EF.

Table 7. Influence of parameters on soil nails.

Parameter		Horizontal displacement	Settlement
Soil	Stiffness	Significant	Significant
	strength	small	minimal
Nail	Bending stiffness	Minimal	Minimal
	Axial stiffness	Significant	Minimal
	length	Significant	Minimal

This is so as there is little soil yielding, and the soil remains essentially elastic making soil stiffness more

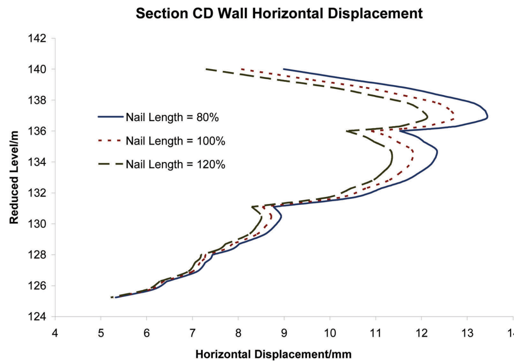

Figure 18. Influence of nail lengths on deflections at CD.

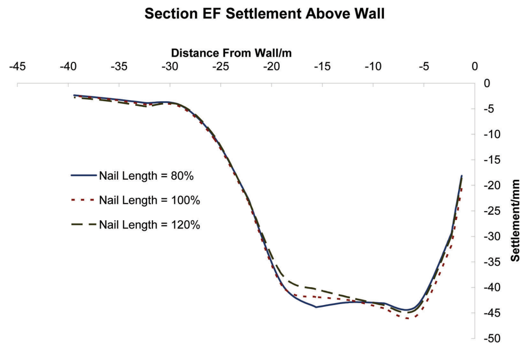

Figure 19. Influence of nail lengths on settlements at EF.

significant than strength in the nail responses. The bending stiffness of the soil nails has little influence on soil nail and ground deformations. Nail lengths has greater influence on wall deflection and little impact on ground settlements.

The findings of this paper are summarized in the following Table 7:

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Tan SA, GR Dasari and Lee CH, 2005, "Effects of 3D soil nail inclusion on pullout with implications for design", Ground Improvement, 9, No.3: 119–125.