

WOOLGOOLGA TO BALLINA PACIFIC HIGHWAY UPGRADE – RELIABILITY ASSESSMENT OF SOFT GROUND TREATMENT DESIGN

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ABSTRACT

Eleven road sections with an approximately 20 km total length out of the 155 km Pacific Highway Upgrade project between Woolgoolga and Ballina (W2B), NSW traverse areas having significant depths of soft soils. At Maclean Interchange or Clarence River Interchange, soft soil thickness was up to 20 – 25 m under the road alignment. Soft ground treatment design for the identified soft soil areas was undertaken in 2014. The main objectives of the soft ground treatment were to provide certainty of delivery of the highway upgrade within a given time during the main contract with a satisfactory long-term pavement performance.

The highway section between Whytes Lane and Pimlico Road of approximately 3.85 km is one of the longest road sections underlain by up to 8 m thick soft soil that required ground treatment. Due to the significantly length of the soft ground treatment for this road section, one of the main objectives was to reduce or optimise the cost of soft ground treatment.

During the detailed design stage, soft ground treatments using preloading with or without Prefabricated Vertical Drains (PVD) were considered. Due to issues such as sample disturbance during soil sampling and transporting, limitations of the adopted soil testing methods and equipment, limitations of the available geotechnical investigation information, there was a possibility that the actual ground behaviour could be different from the predicted behaviour using the design soil parameters. Reliability analyses were carried out to assess the potential variability of material parameters on embankment settlement and ground treatment requirements.

The reliability assessment provided quantitative confident levels of the ground treatment designs and suitable contingency measures. The reliability assessment provided indication of the cost and risk balancing. The target confidence level was minimum 70% for the soft ground treatment design with the proposed observation method and contingency measures such as placement of additional surcharge or additional preloading time to respond to changes during the preloading period. The reliability assessment also effectively assisted the client's decision on the preferred soft ground treatments.

The adopted reliability assessment method as described in Duncan (2000) and the assessment results for the soft ground treatment design were presented. The embankment settlement was monitored during the preloading stage and was back analysed. The reliability assessment results, which were analysed in the design stage, and the ground treatment design were reviewed against the actual embankment settlement performance.

1 INTRODUCTION

Over the approximately 155 km project length from Woolgooga to Ballina, there are a total of eleven highway sections underlain by soft alluvium, with lengths ranging from about 0.5 km to 4 km. The soft soil sections are numbered as Soft Soil Sections 1 to 11. At these areas, soft soil thickness ranges from 5 m up to approximately 26 m depth and extends over kilometres of distance. These soft soil sections are part of Clarence River Floodplain or Richmond River Floodplain.

The highway section between Whytes Lane and Pimlico Road of approximately 3.85 km is one of the longest road sections underlain by up to 6 - 8 m thick soft soil that required soft ground treatment. This soft soil section is called Section 11 in this project. Due to the significantly length of the soft ground treatment for this road section, one of the main objectives of the soft ground treatment design was to reduce or optimise the cost of soft ground treatment.

During the detailed design stage, soft ground treatments using preloading with or without PVD were considered. Reliability analyses were carried out to assess the potential variability of material parameters on embankment settlement and ground treatment requirements. The reliability assessment provided indication of the cost and risk balancing. The reliability assessment also provided quantitative confident levels of the ground treatment designs and suitable contingency measures. The reliability assessment also effectively assisted the client's decision on the preferred soft ground treatments.

This paper first presents a brief site location and geology descriptions of this soft soil Section 11 and the highway upgrade requirements followed by the reliability assessment, and the embankment settlement back analysis results. The adopted reliability assessment method by Duncan (2000) was summarised together with soil parameters. Typical reliability assessment results and associated discussions were presented. Based on the assessment, suitable soft ground treatment using surcharge with PVD was used for Section 11. The embankment settlement was monitored during the preloading stage and was back analysed. The reliability assessment results, which were analysed in the design stage, and the ground treatment design were reviewed against the actual embankment settlement performance.

2 PROJECT INFORMATION

The 3.85 km of Section 11 along the Pacific Highway started from Whites Lane (CH159900) to Pimlico Road (CH163750) is shown in Figure 1. The highway upgrade included embankment widening along the western side of the existing highway to form a two-lane dual carriageway. The new embankment height generally ranged from 1.8 m to 3 m. The detailed civil and geotechnical design of the soft ground treatment was completed in 2014 for a target completion of the highway upgrade at the end of 2019. It was anticipated that 3 years (2015 to 2017) would be available for the early works (EW) soft ground treatment and 2 years (2018 to 2019) would be available for the main construction of the highway.



Figure 1: Location of the highway upgrade soft soil Section 11 (Whytes Lane to Pimlico Road)

3 GEOLOGICAL SETTING

The extent of Section 11 crosses the floodplain of the Richmond River, underlain by thick sandy and clayey alluvium and estuarine sediments of Quaternary (Holocene and Pleistocene) age. The Quaternary sediments were deposited in alluvial, estuarine, and marine environments largely reflecting changes in sea level, which occurred over about the last 250,000 years. The Holocene clay (very soft to firm) thickness ranges from approximately 6 m to 8 m along the highway alignment. The Pleistocene deposits, which underlies the Holocene, comprises of stiff to very stiff clayey soils followed by loose to dense sandy soils to approximately 20 m to 30 m depth. These Quaternary sediments are underlain by residual soils and sedimentary rocks of the Bundamba Group and Neranleigh Fernavle Beds.

Figure 2 shows a typical geotechnical long section along approximately 200 m length of the upgrade highway alignment from CH160950 to CH161250. Soil Units 2c and 2e represent the Holocene soft soils, which is of highly compressible and low permeability. Due to the extensive 3.85 km length of this section, only the representative geotechnical long section of 200 m length has been shown. Other area has relatively similar soft soil unit thickness.

Geotechnical investigation included boreholes and CPTs at approximately 200 m spacing. We considered that the available geotechnical information for the EW design was relatively light over 3.85 km embankment length. However, given the total thickness of the soft soil layers was not excessive and the design embankment height is relatively low the level of geotechnical information for this section was considered acceptable for detailed design of the EW soft ground treatment. During the installation of PVD and monitoring instrument, the geotechnical information was reviewed and confirmed since the construction started in early 2016.

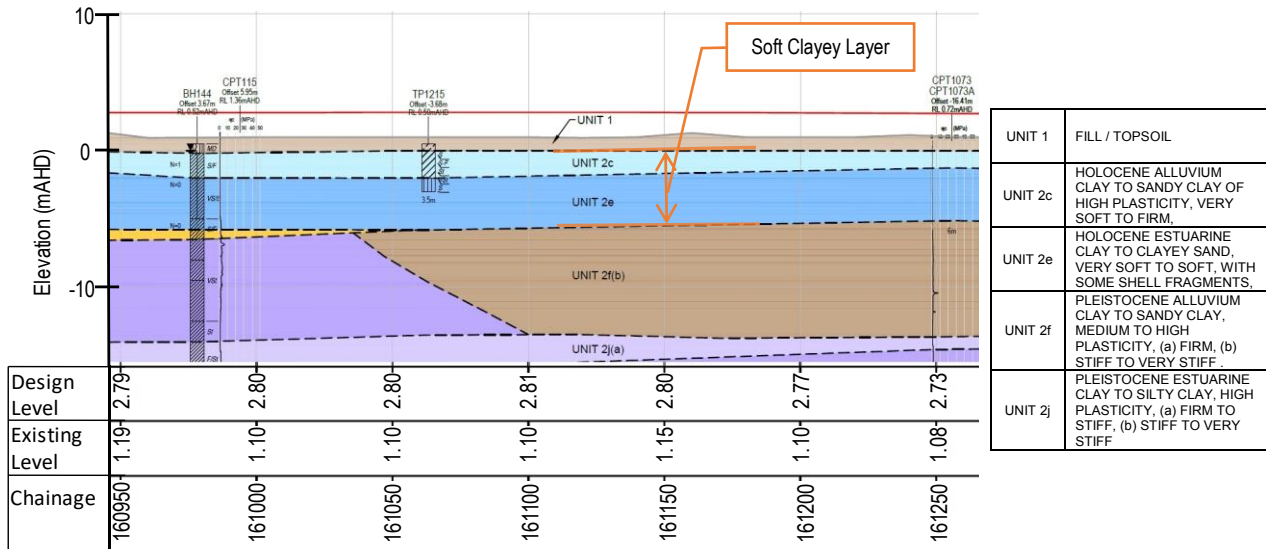


Figure 2: Typical Geotechnical Long Section

4 SOFT GROUND TREATMENT DESIGN

In the EW ground treatment design in 2014, Post Construction Settlement (PCS) criteria over 40 years was 200 mm for general embankment with flexible pavement and 120 mm for culverts respectively. Preloading and surcharge without vertical drains was designed for general embankment section from CH159900 to CH163000. Preloading and surcharge with PVD at 2.5 m centre to centre spacing was designed for embankment sections from CH163000 to CH163750, where there are five proposed new culverts. The available EW preloading time was from 2.5 years up to 3.5 years, inclusive of PVD installation and embankment construction time. Nominal surcharge of 0.4 m to 0.5 m thick fill was allowed in the EW design.

Figure 3 shows a typical cross section of the EW embankment over the proposed widening area adjacent to the existing highway. Soft ground treatment design was carried out using analytical and finite difference methods using the software CAOS (Consolidation Analysis of Soils) developed by Professor Harry Poulos with modification to include post surcharge creep reduction using the method described in Wong (2010). The design considers the following embankment preloading aspects:

- 2-dimensional stress distribution with depth under a fill embankment,
- ground consolidation with PVD including smear effect,
- large embankment deformation and settlement,
- time dependent settlement (creep settlement) and creep reduction due to surcharge removal and over consolidation effect, and
- embankment construction staging.

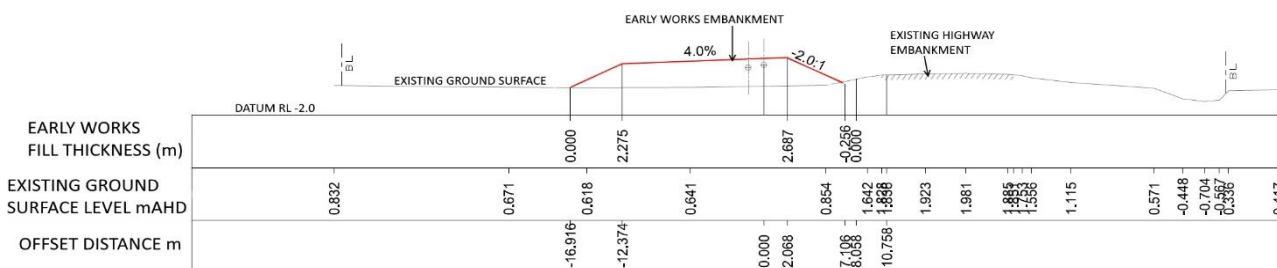


Figure 3: Typical Highway Upgrade Section at CH160,120

5 RELIABILITY ANALYSIS

Due to issues such as limitations of the available geotechnical investigation information, sample disturbance during soil sampling and transporting, limitations of the adopted soil testing methods and equipment, there was a possibility that the

actual ground behaviour could be different from the predicted behaviour using the design soil parameters. The available number of laboratory testing for soft soil layer over this road section were limited, i.e. there were only 6 oedometer test results for 3.85 km embankment length. The geotechnical test locations were at relative wide spacing of up to 200m.

In the EW detailed design, reliability analyses were carried out to assess the potential variability of material parameters on embankment settlement and ground treatment requirements. This section presents the reliability assessment, which was carried out and reported as part of the EW design in 2014. Two representative embankment sections with or without PVD were analysed. Two scenarios of preloading time of 2.5 years and 3.5 years (inclusive of construction time) were considered.

2.1 RELIABILITY ANALYSIS METHOD

Reliability analysis using First Order Reliability Method (FORM), specifically Taylor series method, was adopted to evaluate the effect of uncertainties in the estimated settlements and surcharge. Details of this method and its applications in geotechnical engineering design have been presented by Duncan (2000). In the reliability analysis, the critical soil parameters OCR, CR, CRR, $C_{\alpha e}$, c_h and c_v , thickness of soft soil (Units 2c and 2e), and thickness of the high c_v zone were varied. The steps involved in the reliability assessment are as follows:

1. Assess the Most Likely Values (MLV) of the critical soil parameters involved in the calculation and compute the required settlement and surcharge.
2. Assess the Highest Conceivable Values (HCV) and Lowest Conceivable Values (LCV) of the parameters involved in the calculation.
3. Estimate the Standard Deviations (SD) of the parameters using the “Three-Sigma Rule” approximation. The SD is estimated as $SD = (HCV - LCV) / 6$.
4. Compute the settlement and surcharge with each independent variable increased by one SD and then decreased by one SD from its MLV, while holding other parameters at their MLV. The compressibility parameters CR, CRR, $C_{\alpha e}$ are considered to be dependent variables (i.e. they relate to each other) and therefore the parameters are varied by $\pm SD$ together in this calculation step.
5. Use the computed MLV settlement and surcharge thickness values from Step 1 and the series of values from Step 3, the Coefficient of Variability (CV) of the result is assessed using the Taylor’s series method. The probability that the actual settlement and surcharge may be greater than the computed most likely settlement and surcharge thickness is then assessed based on the Lognormal Distribution reliability index method.

2.2 RELIABILITY ASSESSMENT PARAMETERS

The profiles of MLV, HCV, LCV, SD, and CV values for the critical parameters of soft soil Units 2c and 2e have been identified and shown in Figure 4. At the time of the soft ground treatment design, there were a total of 6 oedometer testing results available for the soft soil units over the entire 3.85 km of Section 11. Due to the low available number of oedometer tests for Section 11, a correlation of compression index with moisture content using the oedometer testing results of soft soil units from other road upgrade sections of this project have been carried out. Figure 5 shows the compression index (CR) against moisture contents from for soft soil units over Sections 4, 5, 8, and 11 of the W2B project. Based on this plot, a site-specific variation of CR with moisture content was established to derive the reliability parameters of compression indices. The OCR profile based on CPT and interpreted undrained shear strength (using corrected vane shear test results and CPT) has been used in the design, and the scatter of results have also been used to assess the MLV(OCR), HCV(OCR) and LCV(OCR) values.

For the extent depth of the high c_v zone derived by the back analysis of the BBA observed embankment settlements, we have adopted the deepest extent depth (HCV) of this zone is 5 m which is corresponding with the back-analysis result. It was reported from BBA design team that the extent depth of the high c_v zone could be up to 7 m. The shallowest extent depth (LCV) of this zone is 1 m, which is the nominal depth of a crust layer near the surface, where high OCR and c_v values are often measured. For each of the soil parameters, the SD values have been estimated so that the corresponding CV are not less than the recommended minimum values of CV by Duncan (2000). The minimum CV values for each of the soil parameters are listed in Table 1.

Table 1: Adopted Values of CV for Reliability Analyses.

Soil Parameters	OCR	CR, CRR, $C_{\alpha e}$	c_v and c_h	Thickness Soft Soil	Depth of high c_v zone
Adopted CV	20%	15%	40%	12% (0.5m - 1.5m)	22%
Duncan (2000)	10-35%	10-37%	33-68%	-	-

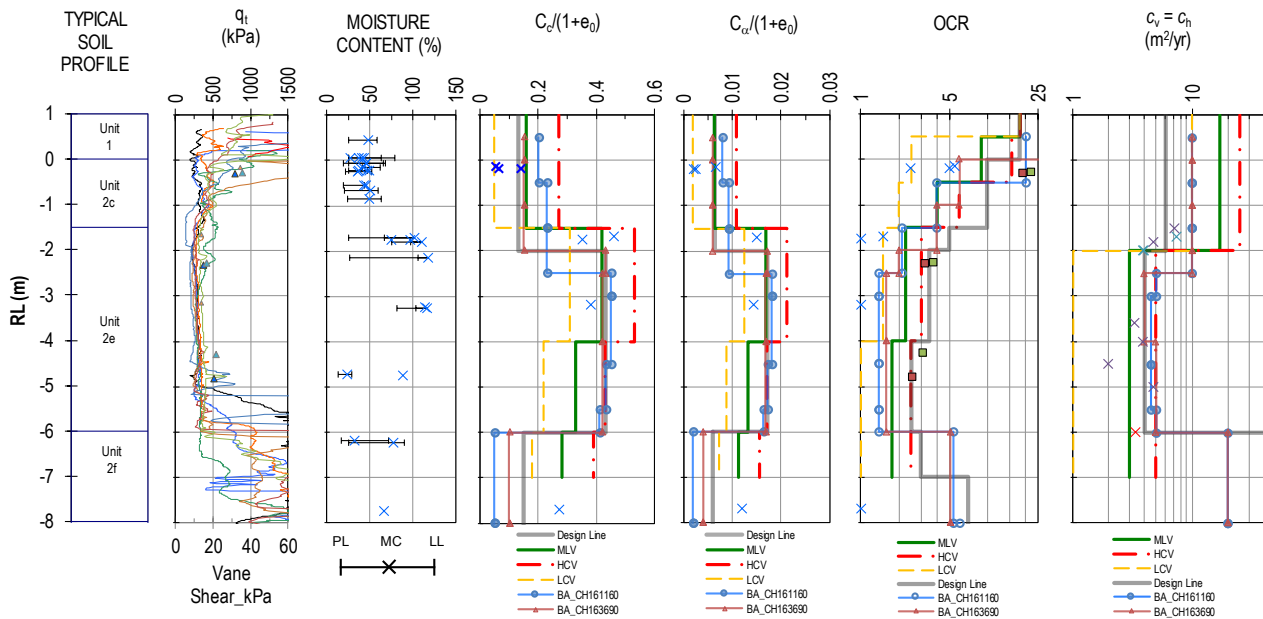


Figure 4: Typical Geotechnical Profile and Parameters

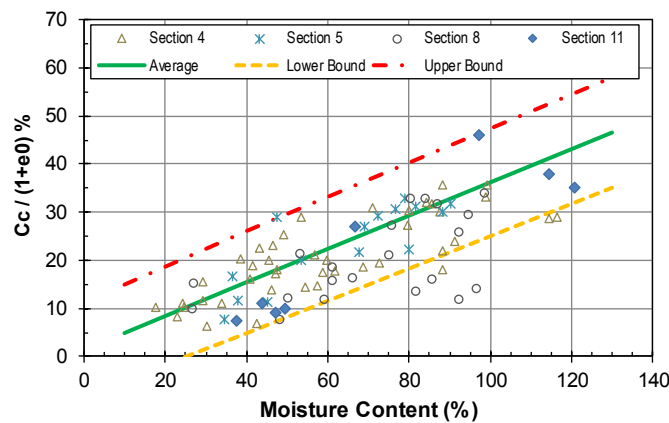


Figure 5: Project Specific Compression Index CR against Moisture Content

2.3 RELIABILITY ASSESSMENT RESULTS

The reliability assessments have been carried out for critical sections with or without PVD using analytical and finite difference methods using the software CAOS. The details and results of reliability assessments for the identified critical sections are shown in Figure 6.

As can be seen from Figure 6(a), the reliability assessment results for embankment settlement at critical sections are generally in the order of 55% confidence over areas without PVD and more than 90% confidence over areas with PVD at 2.5 m centre to centre. The reliability assessment results for preloading settlement indicate that an additional fill thickness of up to 0.3 m above the EW design height may be required to achieve a reliability level of 90% for area without PVD.

Figure 6(b) presents reliability assessment results of the predicted PCS in two scenarios of the assumed preloading periods (2.5 years or 3.5 years). With a preloading period of 2.5 years, the reliability to achieve the PCS criteria for flexible pavement (200 mm / 40 years) would be 74% over areas without PVD and to more than 90% over areas with PVD. The reliability to satisfy the PCS criteria for rigid pavement are relatively lower than that for flexible pavement, i.e. 30% and 50% over areas without and with PVD respectively. An additional 1-year preloading time (increase from 2.5 years to 3.5 years) would increase the reliability to 70% - 87% to achieve the PCS criteria for rigid pavement. In addition, the reliability could be improved by placement of additional surcharge fill thickness and preloading in the main contract (after EW).

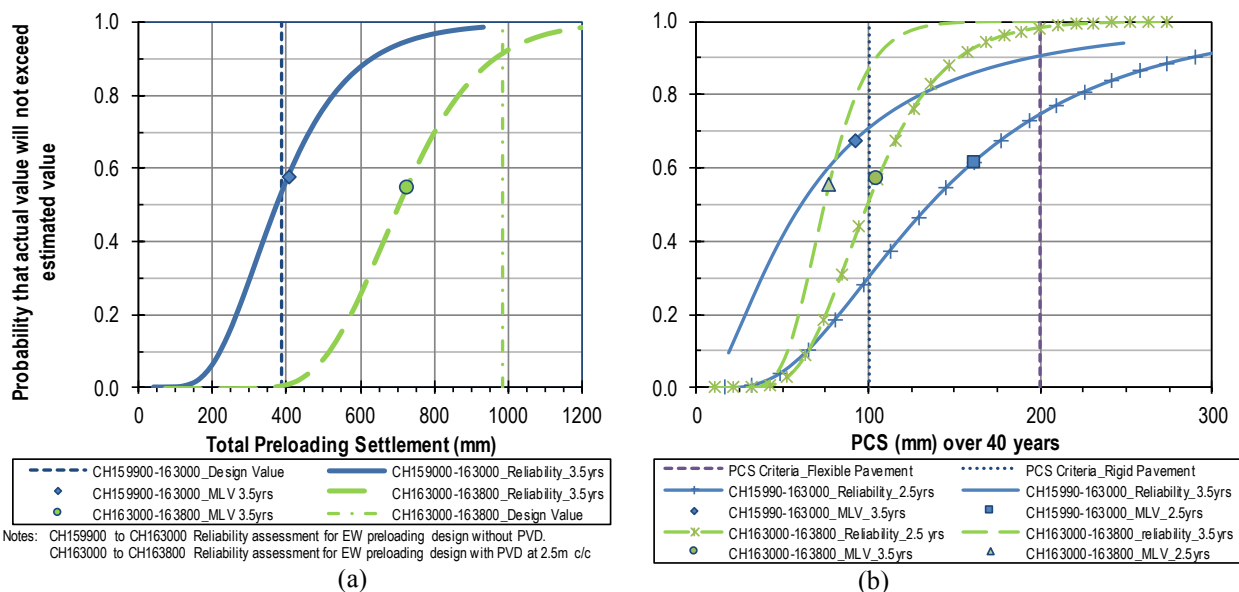


Figure 6: Reliability Assessment Results of Early Works Ground Treatment Design

6 PREFERRED SOFT GROUND TREATMENT

The detailed EW soft ground treatment design for Section 11 was submitted in November 2014. Embankment construction of Section 11 started in early 2016. Because the actual construction for the upgrade over the existing highway and the road widening areas be undertaken in different stages, preloading time of up to 2.5 year or 3.5 years as assumed in the 2014 ground treatment design was not available for the widening. Hence, in early 2016, PC requested Coffey to revisit the design considering PVD for the whole soft soil length of Section 11 with a total construction and preloading time up to 1.5 years.

In the 2016 design, PVD at 1.5 m centre to centre spacing and 0.4 – 0.5 m thick surcharge were specified as the soft ground treatment for Section 11. Based on the reliability assessment results in the 2014 design, it was anticipated that the use of PVD at 1.5 m spacing and preloading with 0.4 – 0.5 m surcharge up to 1.5 years would likely satisfy the PCS criteria for rigid pavement. The expected reliability confidence level of the design would be in excess of 90% for both the preloading settlement magnitude and the predicted PCS over 40 years of operation. The updated ground treatment design was re-issued in March 2016 as the same time as the PVD installation, monitoring instrument installation, and embankment construction. Review of the installation records showed relative consistence of the soft soil thickness with that was assumed in geotechnical design.

7 SETTLEMENT MONITORING AND BACK ANALYSES

Figure 7 shows the monitored embankment thicknesses and settlements with time and with the project alignment chainage from CH159900 to CH163750. The final settlement reading was at 14 December 2019, which was assessed to reach 90% to 95% consolidation completion of the ground. The predicted preloading settlement in the design was also plotted against the chainage. The predicted preloading settlement generally close to the monitored settlement, except approximately 700 m embankment length between approximately CH161000 and CH161700, where the monitored settlement was about 200 mm higher than the prediction. This observation indicated that there was a variation in the soft soil stiffness along the alignment. Under relatively similar fill and soft soil thickness between section CH161000 - CH161700 and section CH161700 – CH162500, the former settled approximately 100 mm to 150 mm more than the later.

Back analysed settlement results of the settlement plates and nearby extensometers at approximately CH161100 and CH163700 are shown in Figures 8 and 9. The back analysed soil parameters are shown in Figure 4. PVD disturbed (smear) zone has been considered in the back analyses. The radius of the smear zone was assumed as twice as that of the band drain PVD. The ratio of the undisturbed soil permeability to the smear zone permeability was assumed as 4.5.

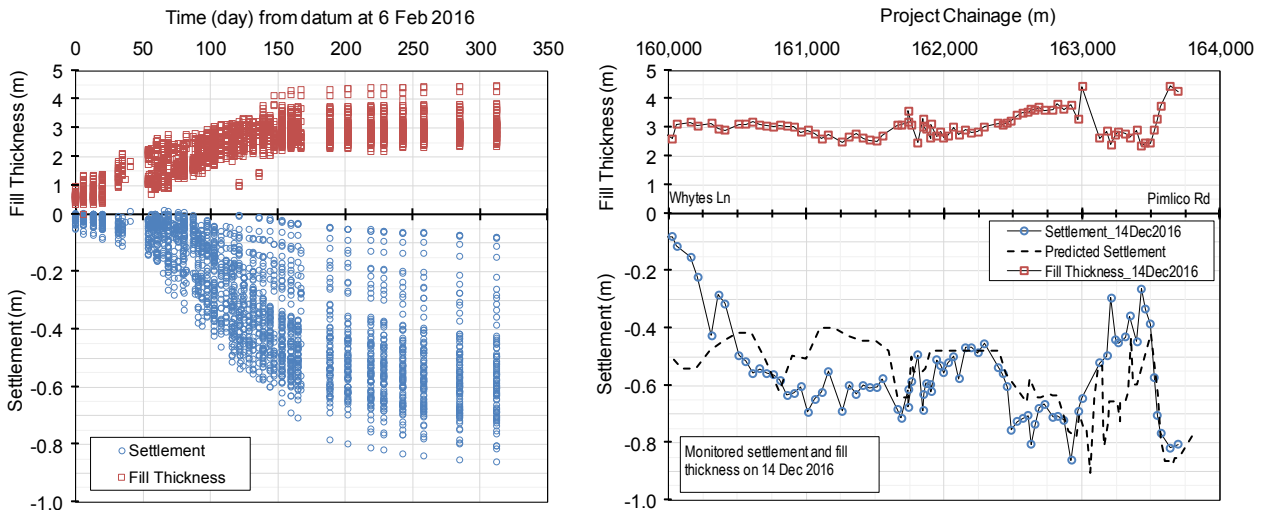


Figure 7: Monitored Ground Settlements

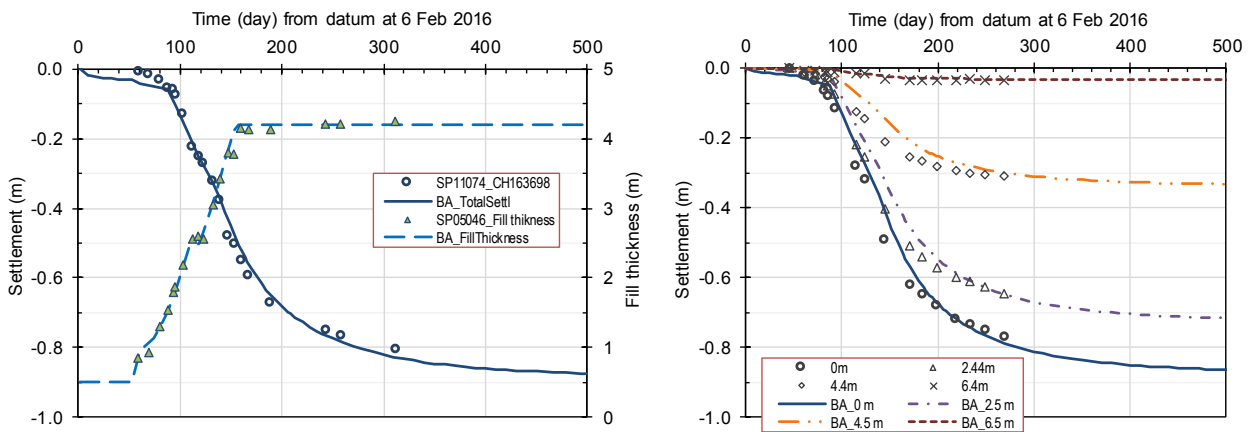


Figure 8: Settlement Back Analysis at CH 163700 (Settlement Plate & Extensometer)

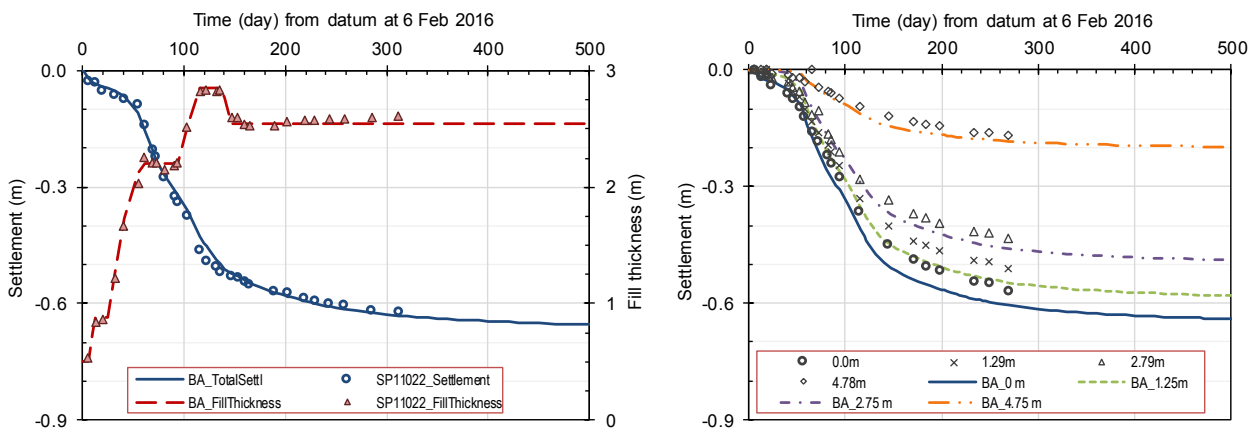


Figure 9: Settlement Back Analysis at CH161,100 (Settlement Plate & Extensometer)

8 BACK ANALYSIS VERSUS DESIGN

What would the PCS have been if the EW design using preloading for 2.5 to 3.5 years with 0.4 – 0.5 m surcharge but without PVD for embankment area from CH159900 to CH163000 was constructed? Would the minimum confident level of 70% for a soft ground treatment design successfully meet the design criteria? To answer these questions, a hypothetical

settlement analysis (without PVD) was carried out for the back analysed embankment section at CH161100 using the back analysed soil parameters.

Figure 10 shows the hypothetical analysis results of the preloading settlement and the forward PCS prediction. The predicted preloading settlement could have been approximately 500 mm or 600 mm at 2.5 years or 3.5 years preloading. The forward prediction of PCS could have been 185 mm/40 years for the former and 125 mm/40 years for the later. According to the reliability assessment in Figure 6 for preloading without PVD, a design settlement with reliability confidence of 80% to 90% would likely be the required minimum level to meet the monitored preloading settlement. For the predicted PCS, a confidence level of 70% - 80% would be sufficient to meet the PCS design criteria.

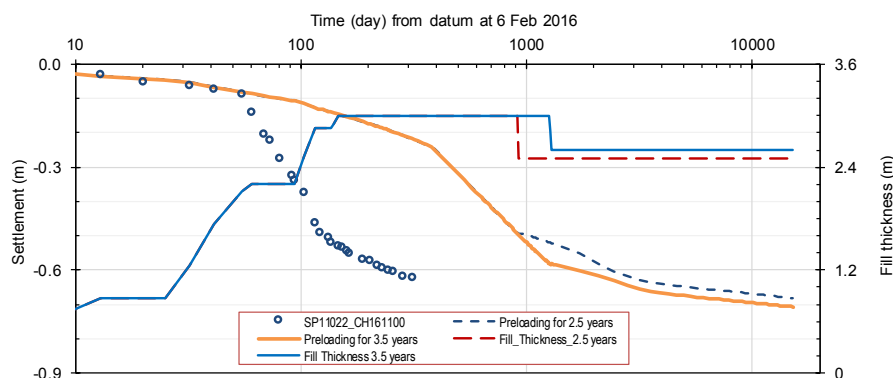


Figure 10: Hypothetical Settlement Analysis at CH 161100 with Back Analyses Soil Parameters without PVD

9 CONCLUSIONS

During the soft ground treatment design stage, reliability assessment was adopted to evaluate the effect of uncertainties in the estimated settlements and surcharge. It is important that reasonable soil parameters be derived for the design and reliability assessment. Site specific soil stiffness parameters have been correlated using the available geotechnical testing results from the project. The adopted variability ranges of soil parameters in the reliability analyses were within the recommended variability ranges by Duncan (2000).

The reliability assessment provided an indication of the design confidence level and the potential contingency measures such as applying additional fill or extending preloading time that may be required depending on the monitoring results. The reliability assessment effectively assisted the client's decision on the preferred soft ground treatments.

Back analyses of the monitored embankment settlement during construction and preloading was carried out and compared very well with the design. The monitoring indicated that the soft ground treatment for the widening embankment was successfully designed and constructed. The predicted forward PCS predictions are within the design criteria for flexible pavement.

10 ACKNOWLEDGEMENTS

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