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Design, monitoring and back-analysis of highway embankments constructed over soft soil

A. Podnar[1]

[1]Douglas Partners Pty Ltd, 96 Hermitage Road, West Ryde, NSW, 2114, Australia, +61 9809 0666; email: adam.podnar@douglaspartners.com.au

ABSTRACT

The Pacific Highway is a highway between Sydney and Brisbane in Australia. It is currently being upgraded to a dual carriageway for its entire 1000 km length. The soft soil embankment design and transition zone design for one of the upgrade sections is presented herein. Due to the limited amount of reliable laboratory data and low embankment heights, the settlement was calculated using the coefficient of volume change, particularly from correlations from CPT results. A short construction programme necessitated the use of a combination of surcharge and wick drains. An in-house spreadsheet calculated the post construction settlement based on the ground conditions in each filled region based on applied ground treatments. Additionally, a unique transition zone solution was used for the bridges in this section of the highway which involved the use of driven piles at increasing spacings away from the bridge abutment. Construction survey data from both embankment settlement and transition zone settlement indicated that the design methods and ground treatments were effective provided a reasonable estimation of the actual ground behaviour.

Keywords: consolidation, wick drains, surcharge, transition zone, back-analysis, construction monitoring

1 INTRODUCTION

This paper presents a summary of the design, monitoring and back-analysis of highway embankments and bridge abutments on soft alluvial soils. The project is an upgrade of a 26 km long section of the Pacific Highway, between Frederickton and Eungai, in NSW, Australia which was designed and constructed by Thiess Contractors (later Leighton Contractors) for NSW Roads and Maritime Services (RMS). Douglas Partners (DP) provided geotechnical advice to Thiess during the tender period and were then appointed as geotechnical designers for the project. During construction DP provided geotechnical advice to the contractor and analysed the results of monitoring.

The RMS specification for the project included very tight criteria for settlement of embankments constructed on compressible soils, namely post construction settlements of less 15 mm and pavement changes in grade of less than 0.3%.

While the geotechnical investigations for the project included numerous boreholes, test pits and cone penetration tests (CPTs), the amount of laboratory testing which had been undertaken to measure the compressibility of the soft soils was very limited. Given that there was more than 5 km of the highway underlain by different sections of soft soils with varying depths and lateral extents, the limited laboratory testing was considered insufficient to adequately profile the soft soil layers. Further, environmental constraints prevented additional field testing and subsequent laboratory testing being completed in time for final design.

DP adopted a pragmatic approach to the problem by identifying that the CPTs provided the best available information on the soft soils and used correlations between the CPT data and soil properties to develop models for use in estimating settlements under the fill embankments. DP used these models to devise ground treatments to allow construction of the fills during the tight 2 year construction time frame and also designed transition zone treatments at bridge abutments to allow for a gradual increase in settlement away from the bridges.

During construction DP used the results of monitoring to refine the design models and material properties to allow prediction of post construction settlements.

2 EMBANKMENT SETTLEMENT DESIGN

2.1 Settlement Method and Parameters

The consolidation settlement under the fill embankments was calculated using the one-dimensional consolidation theory with the coefficient of volume change (m_v) method. The advantage of this method for this project was that correlations between m_v and CPT data could be used to allow values of m_v to be estimated at every CPT location and at 20 mm depth intervals. While m_v values for a particular soil change under different applied stresses, the correlations used were considered appropriate for the relatively small changes in stresses expected under the low fill embankments, which were mostly less than 4 m high.

The magnitude of the consolidation settlement was calculated from m_v values derived from correlations with CPT cone resistance (q_c) using a DP in-house method and a correlation proposed by Sangrelat 1972. The m_v values obtained from these correlations were compared to any oedometer results in the appropriate stress range and the limited dilatometer (DMT) test results. The settlement duration was calculated using $c_{v/h}$ obtained from a relationship between m_v and C_v using a data-matched hydraulic conductivity (from oedometer results), oedometer results and CPT dissipation tests. Creep settlement was calculated using C_α obtained from a correlation between m_v and C_α (Mesri 1994) and those oedometer test results that extended beyond the primary consolidation stage. An improvement in the creep coefficient as a result of surcharge was calculated using a method suggested by Conroy 2010, where the improved creep coefficient is given by:

$$C_\alpha' / C_\alpha = 1.823 - 1.094 \text{ Log } (\sigma_{vs}' - \sigma_{vf}')/ \sigma_{vf}' \qquad (1)$$

Where: C_α'= 'improved' creep coefficient; C_a = creep coefficient; σ_{vs}' = surcharge stress; σ_{vf} = final stress.

The design process included generating geological long sections for each of the soft soil areas and identifying regions with similar geotechnical properties and embankment loadings. The CPT results for each of these regions were plotted and interpreted geotechnical parameters were derived for each layer. For design purposes both 'average' and 'conservative' (or sensitivity check) subsurface profiles were generated for each region. A typical graph of the interpreted parameters for each region is included in Figure 1.

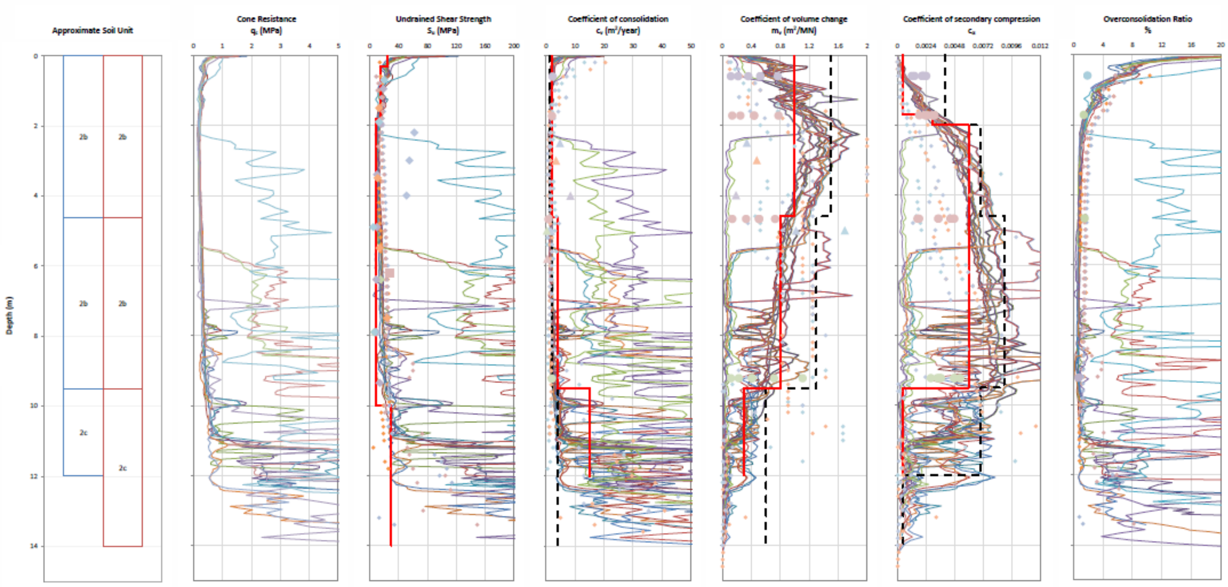

Figure 1. Graphed interpreted parameters for a typical soft soil region (red line = "average", black dotted line = "conservative")

In the design the ratio of the horizontal to vertical coefficients of consolidation (C_h / C_v) was conservatively taken as one. This was due to the lack of specific testing information for the project which meant that there was no evidence to justify a higher horizontal coefficient as commonly occurs in alluvial deposits. The few test nearby dissipation tests and oedometer results suggested this was a appropriate assumption.

As there were many fill sections with individual subsurface profiles, the resulting parameters have not been reproduced here. There was a wide variability between even nearby alluvial deposits.

All the fill regions were analysed to estimate the post construction settlement assuming no ground treatment was applied. For those areas where the predicted post construction settlement was greater than 15 mm (defined as ‘compressible’ soil) ground treatment was required. The settlement calculations included an embankment creep value of 0.1% per log cycle, which accounted for about two-thirds of the allowable settlement for a 4 m high embankment over 40 years, which meant that the ground treatment had to virtually eliminate any post-construction consolidation settlement.

2.2 Ground Treatment Options

Given the extensive areas of fills underlain by soft soils (more than 5 km length) the project team decided to use a combination of wick drains and surcharge to accelerate the consolidation settlement. The tight two-year construction programme for the project meant that a maximum of 6 months was available for surcharging the fills.

DP analysed each of the soft soil sections to optimise the height and duration of the surcharge and spacing of wick drains required to ensure that the post construction settlement complied with the project specifications.

In the design of the wick drains the diameter of the wick drain smear zone was conservatively taken as $3d_w$ (d_w = wick drain diameter) and the ratio of undisturbed permeability versus smeared permeability (k_h / k_s) was taken as 2.

2.3 Calculation Method

For each of the soft soil sections the subsurface profile from CPT data, interpreted geotechnical parameters and ground treatment options were analysed using an in-house spreadsheet developed for and further refined throughout the project. The calculation time for full analysis of the 19 ‘compressible’ fill regions was about 10 seconds. As additional field investigations were undertaken, the new geotechnical data was able to be included quickly and optimisation of the treatment options assessed. This resulted in subsequent savings in both construction programme and cost.

3 TRANSITION ZONE DESIGN

3.1 Problem Characterisation

A significant portion of the Pacific Highway in northern NSW is built over flood plains and is underlain by soft soils. Transitioning between relatively large settlements under fill embankments to negligible settlements at bridges founded on piles has historically presented both a comfort issue for motorists and ongoing maintenance issues at bridge approaches. For this project the, post construction change in grade was required to be limited to 0.3% with less than 50 mm post-construction settlement within 50 m of any bridge abutment.

3.2 Design Concept

The solution devised for this project to transition settlements beneath bridge abutments used driven piles founded in stiff to hard clays with increasing spacing moving away from the bridge abutment. In order to allow arching between the pile caps, a load transfer platform of rockfill and geogrids was used.

3.3 Detailed Design

The software package PLAXIS® was used to confirm the viability of and refine the transition zone design. A pile spacing was chosen to allow a gradual increase in the amount of load from the fill embankment which would be transferred to the soil between the piles and this, together with the load transfer platform of rockfill and geogrids, was modelled for each transition zone for each bridge abutment. The proposed construction schedule was modelled, including application of surcharge and wick drains in the adjacent embankment.

For some bridge abutments the results of the analysis indicated that it would be better to decrease the length of piles which were further away from the bridge abutment. Additionally, localised ramped height surcharge was applied in order to smooth the post construction settlement change in grade.

A general arrangement of a transition zone model is presented in Figure 2.

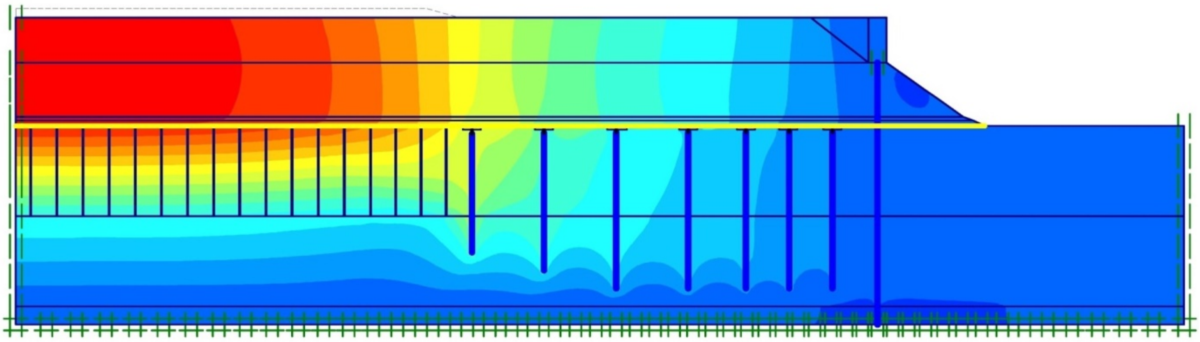

Figure 2. General arrangement of bridge transition zone

4 CONSTRUCTION PHASE SETTLEMENT

4.1 Survey Results

Under the contract instrument monitoring arrays were required to be installed every 100 m in areas underlain by ‘compressible’ soils. These arrays typically included settlement plates (x3), vibrating wire piezometers, horizontal profile gauges and inclinometers. These instruments were read at regular intervals before, during and after embankment construction. The monitoring results were made available to DP and the client through an online database.

Additionally, a graph of driving resistance over the depth of installation was supplied from the wick drain installation rig for each of the 70,000 wick drains installed on the project. Review of the information provided by the wick drain sub-contractor showed that the absolute magnitude of the driving resistance varied significantly and appeared to be uncontrolled, but there was a very apparent inflexion point in all the resistance data which showed the depths to the base of the soft soils. These depths were checked against the information from CPTs undertaken immediately adjacent to specific wicks. The interpreted depths to the base of the soft soils from each of the wick drains, together with the supplied co-ordinates, were used to map the depths of soft soils under the fills using GIS.

An example of the output from this information is presented in Figure 3. The figure shows that the soft soil profiles varied in thickness both along and across the fill areas. This data was compared to the interpreted profiles used in the design and, where necessary, the ground treatment was varied to suit the actual ground conditions.

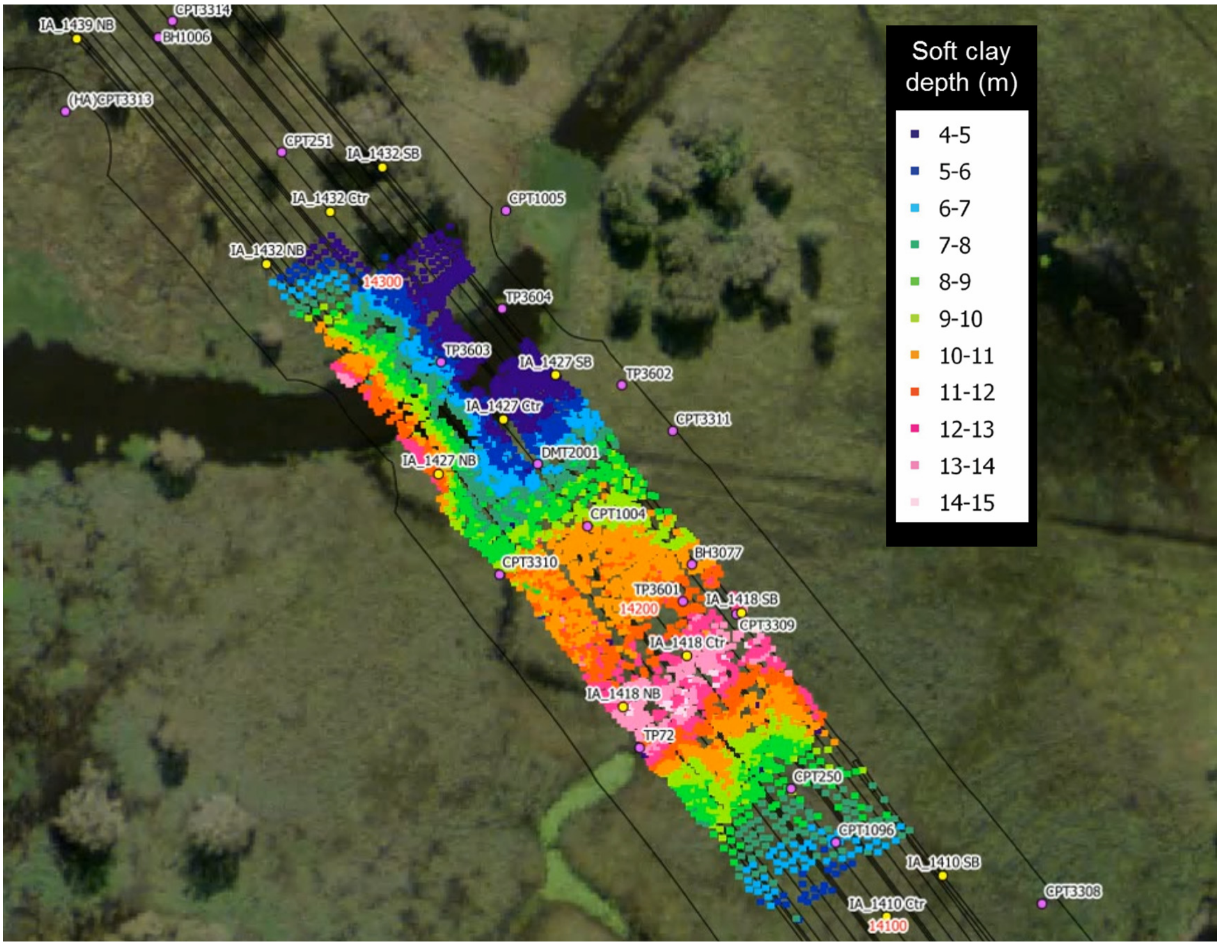

Figure 3. Soft clay depths based on wick rig installation logs

4.2 Back Analysis

An observational method was adopted for the project in which the actual settlements monitored during construction were progressively fed back into the design model to refine the predictions of post-construction settlement. This presented both an opportunity and a risk during construction that the durations of surcharge could be reduced or might be required to remain in place for a longer period.

With the additional information obtained from the wick drain installation, the settlement measured at each of the settlement plates were back-analysed to compare predictions and then to predict future performance. A further refinement to the analysis undertaken during construction was that the actual construction stages (fill heights and timing) were included in the analysis of the measured settlements.

Generally, the choice of relatively conservative parameters during design meant the settlement magnitudes were slightly overestimated (in the order of 10% - 20% in the regions with the most settlement). Similarly, the settlement durations were typically overestimated by about one order of magnitude for the same regions.

After slight modifications to layer thickness and interpreted soil properties all the measured settlements could be matched to settlement predictions for the interpreted soil profiles at each location. An example of one of the settlement predictions with the actual measured settlements results overlain is shown in Figure 4.

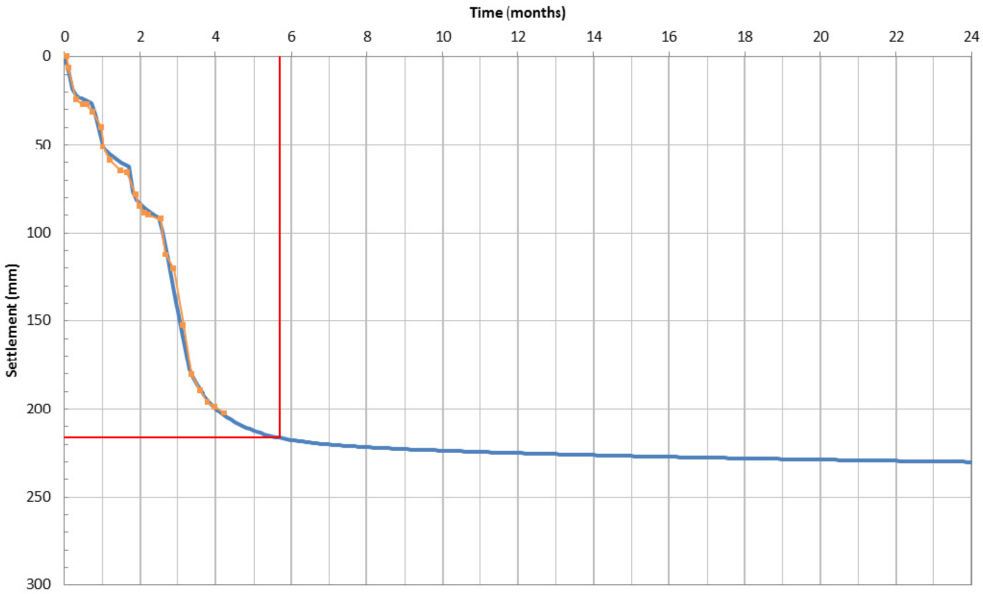

Figure 4. Example result of the settlement back-analysis (actual settlements shown in orange with predicted settlements shown in blue)

A report was prepared for each fill region using the results of the back analysis to recommend the length of time the surcharge should remain in place. Generally this surcharge period was either the same or slightly shorter than the surcharge period assumed during the detailed design. For one fill only the back-analysis indicated that the surcharge needed to remain in place for longer than the design assumed. The reports for each section were reviewed by both the client (RMS) and the project verifier prior to removal of the surcharge.

5 CONSTRUCTION PHASE TRANSITION ZONES

Instrument arrays were also installed within transition zones adjacent to bridge abutments. As expected, minimal pore pressure response was encountered in vibrating wire piezometers within the piled section of the transition zones which showed that the loads from the fill embankments were being effectively transferred to the piles. The settlement plate readings at the end of the surcharge period were compared to the analysis results from the same time period. An example of a well-matched prediction showing a gradual increase in settlement away from the bridge abutment is shown in Figure 5.

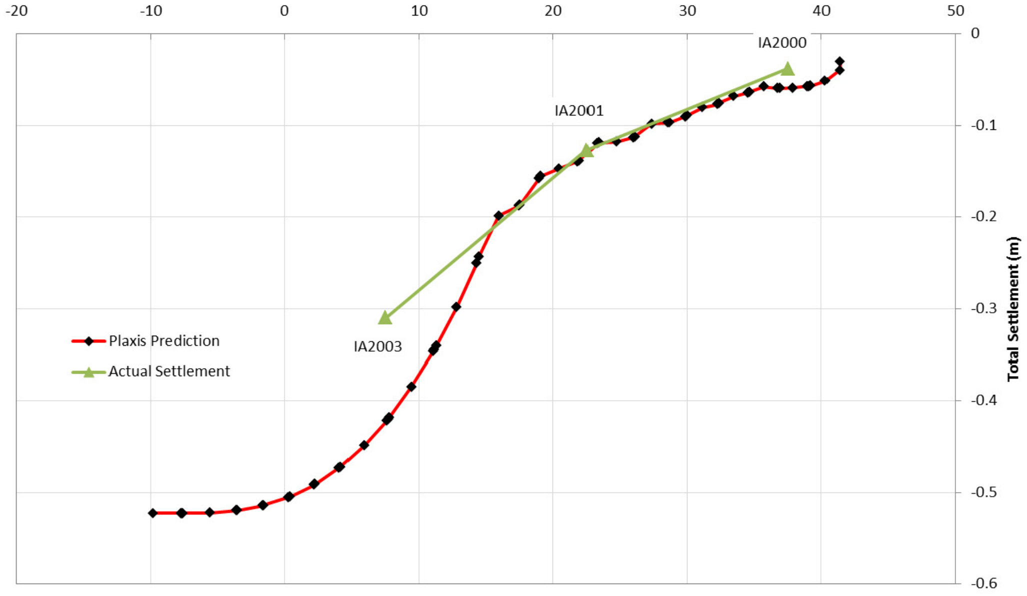

Figure 5. Comparison between predicted behaviour and surveyed results in transition zone

While not all predictions were as close to surveyed measurements, all surveyed results showed proportionally increasing settlement away from the bridge abutment, consistent with the design logic.

6 CONCLUSION

The availability of CPT test data and very limited laboratory test results for soft soils encouraged the use of correlations between CPT data and compressibility to be used on this project to predict settlements and allow design of ground treatments. While the adoption of slightly conservative parameters during design resulted in slightly conservative predictions of settlement, the monitoring of settlements during construction and back analysis of the actual settlements to refine the geotechnical models were successfully used to control the timing of surcharge removal and allow prediction of future settlements.

The results of monitoring during construction show that the design of the transition zones for the project using piles at increasing spacings, together with a load transfer platform of rockfill and geogrids, effectively managed the settlement such that it gradually increased away from the bridge abutments.

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