CONSOLIDATION AND CREEP OF SOFT ESTUARINE CLAY IN NEWCASTLE

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ABSTRACT

Soil mixing and other intrusive ground improvement techniques are often go-to solutions for problematic soft soils. However, it is very much worthwhile to undertake detailed project specific studies and use advanced constitutive soil models to demonstrate that expensive ground improvement techniques are not always required. This paper looks at a case study where the Soft Soil Creep model was used in Plaxis to simulate the soft Estuarine Clay found at Kooragang Island, Newcastle and proves that deep soil mixing is not necessary for a rail embankment design. A review of field/laboratory tests and back analysis of field monitoring data from a trial embankment were undertaken to derive design parameters of the Estuarine Clay and understand its consolidation and creep behaviour. Site history and aging of the Estuarine Clay were then modelled using Soft Soil Creep model in Plaxis, which allows calibration of the stress state conditions at present time with field conditions. The calculated soil strength profile and past ground movements were able to be correlated with available data including cone penetration tests, shear vanes, inclinometer and extensometer readings. Predictions from the Soft Soil Creep model demonstrate a more sensible representation of current site conditions compared with using basic soil models. This realistic design approach assures confident in optimising the rail embankment design, which brings massive savings on construction costs from eliminating the need for deep soil mixing. The use of an appropriate advanced constitutive soil model, combined with a rigorous study of site specific data, has proven to reduce conservatism in design and increase the substantially benefit of real projects.

1 INTRODUCTION

Soil behaviour is very much complex and often difficult to predict. It is common in design projects to use conventional soil models in order to simplify the interpretation of material properties and predictions. In doing so, conservatism is frequently introduced leading to a costly over-design. Whilst it is often justifiable and beneficial to simplify the problem and analysis, saving time and costs during the design phase to offset construction costs, there are situations where this is not possible due to specific constraints. In this case, attempting to model the realistic soil behaviour with an advanced soil model may be the solution. This paper looks at a rail project at Kooragang Island, Newcastle as a case study where the advanced Plaxis Soft Soil Creep model, combined with targeted site investigation and rigorous site specific study, were utilised to more realistically simulate the behaviour of the soft Estuarine Clay. The benefits of the design approach were able to overcome the constraints of the project and significantly reduce risks and construction costs.

The current rail configuration of the Kooragang Coal Terminal (KCT) Arrival Roads is not capable of processing the required volume of trains to meet demands. An additional rail track is required adjacent to existing rail tracks in order to improve the operational capacity of the coal terminal at Kooragang Island. At the location of this case study, there are currently two existing rail tracks (one for arriving and one for departing rail vehicles). The existing rail tracks are situated on an approximately 2 m high embankment consisting of slag material. This existing rail embankment was constructed in the early 1980's and has been operating for over 30 years and withstood the 1989 Newcastle earthquake (McCue et al., 1990).

There are several critical constraints that complicate the construction of the proposed rail embankment. First and foremost is the presence of very soft to soft Estuarine Clay (including up to 14 m thick at a deep infilled paleo-channel), which could potentially result in excessive settlements beyond the rail operation tolerances, as well as trigger a global slope instability as the slip circle shears through this soft layer. Secondly, an existing high pressure gas pipeline runs parallel along the existing rail embankment with an approximate 8 m to 10 m offset from the toe of the existing embankment slope. This limits: 1) the construction area/boundary; and 2) stress and deformation effects imposed by the proposed embankment on the pipeline.

In addition, other natural and man-made constraints to the development of the proposed embankment include:

- The variability of the existing dredged sandfill, slag and mixed fill reclamation;
- Construction of the new embankment adjacent to live operating rail traffic;
- Endangered ecological communities wetlands area;

- Low lying swamp bounded by the existing Kooragang Island reclamation and rail infrastructure;
- Natural watercourses and creeks including the tidal Moschetto Channel crossing which abuts the Kooragang Island reclamation along the alignment; and
- Potential asbestos contaminated material within the existing embankment.

2 GEOLOGY OF KOORAGANG ISLAND IN NEWCASTLE

Kooragang Island is located north of Newcastle near the mouth of the Hunter River estuary extending upstream to Hexham. Originally Kooragang Island was subdivided into smaller former islands by mud flats and various subsidiary channels, such as the Moschetto Channel and the former Rotten Row. Industrial development in the 1960's led to dredged sand fill reclamation, which amalgamated the former islands into the current larger Kooragang Island. It now mainly splits the Hunter River at Hexham into two main channels, namely the North and South channels, which surrounds the island.

The project site area (Figure 1) for this case study comprises a section of land reclamation abutting natural swamp area and mangroves. The site covers channel infill, including the truncated Moschetto Channel and an old paleo-channel along a buried previous course of the Moschetto Channel.

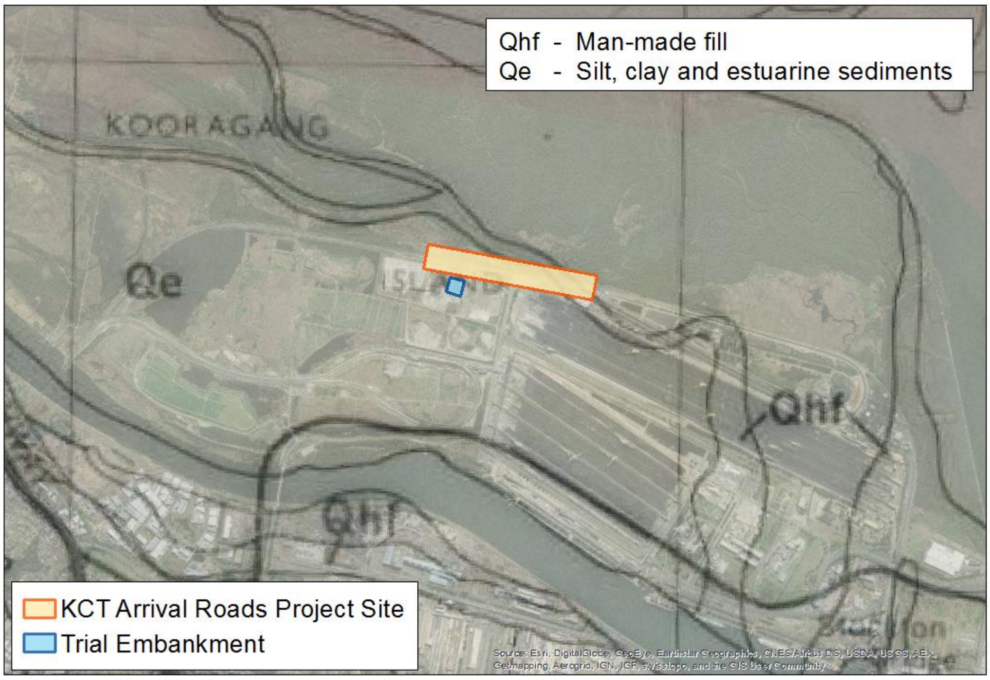


Figure 1: Project site location and geology

A series of ground investigations have been undertaken at the project site, which include conventional borehole drilling, test pit excavation, Cone Penetration Test (CPT) and hand shear vane test. The existing rail embankment is situated on recent soft Estuarine Clay deposits, which are known to be up to 14 m thick at the location of the old paleo-channel before reaching the more competent Estuarine Sands. The upper 3 m of the Estuarine Clay material is generally a more competent crust layer. Towards the Moschetto Channel, the embankment sits on dredged sand fill, which overlies the Estuarine Clay. The rail embankment itself is made of a mixture of very dense slag and reclamation fill material. Since the 1960's, the existing ground is expected to have undergone through considerable consolidation under the existing rail embankment and live heavy rail loads. Figure 2 illustrates the existing ground profile at the site location.

3 ORIGINAL DESIGN: GROUND IMPROVEMENT OF SOFT ESTUARINE CLAY

3.1 GROUND IMPROVEMENT BY DEEP SOIL MIXING (DSM)

The philosophy of the original earthworks design was to adopt deep soil mixing (DSM) using the dry soil mix technique to improve the shear strength and limit compressibility of the Estuarine Clay under the proposed embankment extension, as illustrated in Figure 2. A gravity retaining structure would then be constructed on the improved ground to support the proposed rail embankment.

The ground improvement would provide: 1) a suitable foundation for the proposed retaining structure and rail embankment extension with the additional rail track; 2) achieve an acceptable level of ground deformation and embankment stability of the existing and proposed rail embankment; and 3) limit the impacts of the proposed embankment on the existing gas pipeline within the allowable criteria.

Ground improvement would normally have been appropriate, as have been previously utilised on numerous occasions on Kooragang Island, including the Newcastle Coal Infrastructure Group (NCIG) projects (Hawkins et al., 2008 and Chua et al., 2008). However, there are other site specific constraints and considerations including: 1) the existing gas pipeline and environmentally protected mangrove wetland areas are in close proximity which restricting working space of large and heavy equipment; 2) a large and heavy DSM rig was foreseen to have access issues and potential adverse risks on the gas pipeline and the live operating rail traffic; 3) the installation of the DSM columns would require cutting a large volume into the existing potentially asbestos contaminated embankment which requires special disposal; and 4) the existing embankment was constructed with slag material which is considered more competent than the new embankment fill; that limit the constructability of the original ground improvement scheme and it was inevitably another design solution had to be put forward.

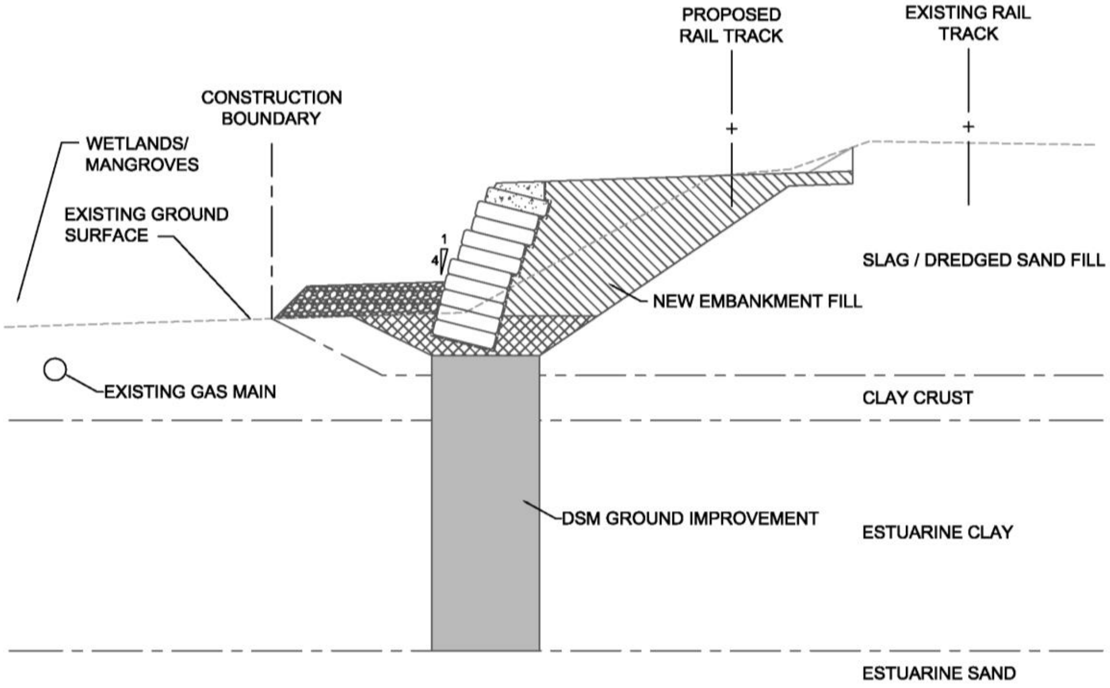


Figure 2: Illustration of original ground improvement design

3.2 CONSERVATISM IN THE ORIGINAL DESIGN

Ground improvement was initially proposed following slope stability analysis of the proposed rail embankment using simple Mohr-Coulomb soil model. The analysis indicated that the proposed embankment without any ground improvement would have factors of safety (FOS) less than 1.5 (minimum required for the project). Based on this finding DSM was proposed. An issue was later uncovered following further review of the modelling approach.

The undrained shear strength parameter of the soft Estuarine Clay was determined from available ground investigations (CPTs and in-situ shear vane tests being the most applicable). It is expected that the soft Estuarine Clay layer immediately beneath the existing embankment will have a higher shear strength due to consolidation over time from the rail and embankment surcharge, and decreasing further away from the embankment toe. With the intention of replicating the gradient of the soil strength profile, the soft Estuarine Clay was divided into three zones (immediately beneath the existing embankment, transition zone beneath the existing slope batter and natural wetlands side). This was a reasonable approach; however, was found to be conservative. The ground investigations that penetrated to sufficient depths to have meaningful indication of the Estuarine Clay’s undrained shear strength were only available at the wetlands side or at the toe of the existing embankment. The absence of any meaningful data immediately under the existing embankment prevents the accurate interpretation of the true undrained shear strength of the Estuarine Clay beneath the existing embankment. This conservatism was confirmed when the stability analysis resulted in factors of safety between 1.1 and 1.2 for the existing embankment, when site observations suggested the slope had been performing well and had withstood the 1989 Newcastle earthquake measuring 5.6 on the Richter scale (McCue et al. 1990).

A Plaxis 2D model was developed using the Soft Soil model for the Estuarine Clay to predict ground settlement in the original design. Unlike the Soft Soil Creep model (discussed in the next chapter), the Soft Soil model does not account for strengthening of the soil due to creep and relies on the current over-consolidation ratio (OCR) of the soil to determine its stress state. The OCR was derived from available CPTs. However, similar to issues with the slope stability analysis, no meaningful data was available immediately beneath the existing embankment for accurate OCR input to the Soft Soil model.

4 MODELLING WITH SOFT SOIL CREEP MODEL

4.1 PLAXIS SOFT SOIL CREEP MODEL

The Plaxis Soft Soil Creep model is an advanced constitutive soil model, which differentiate the soil behaviour under primary load and unload/reload, like the more commonly used Hardening Soil and Soft Soil models (Waterman and Broere 2004). The Soft Soil Creep model applies a cap in the stress space to delineate the limit stress state. The initial cap is first established by the pre-consolidation stress, and expands over time due to the creep component being modelled. The cap is hence a function of the soil stress state and time. Any change in the soil stress state will affect the rate at which the cap expands. The cap, however, will always continue to expand (at a decreasing rate) simulating the improvement effect of the soft soil from creep over time.

The key parameters used in the Soft Soil Creep model include the modified Cam-Clay parameters, i.e. modified compression index (λ^*), modified swelling index (κ^*) and modified creep index (μ^*). These parameters are related to common soft soil compressible parameters C_c, C_s and C_α respectively as presented in Equations (1), (2) and (3). In addition, the Soft Soil Creep model is also sensitive to the permeability (k) and change of permeability (C_k) of the material.

$$\lambda^* = \lambda/(1+e) = C_c/[2.3(1+e)] \tag{1}$$

$$\kappa^* = \kappa/(1+e) = 2C_s/[2.3(1+e)] \tag{2}$$

$$\mu^* = C_\alpha/[2.3(1+e)] \tag{3}$$

With consideration of the above, it is paramount that the site history is well understood and modelled in order to develop the correct soil stress state at the present time. For this project, firstly the Soft Soil Creep parameters were calibrated with monitoring data recorded from a trial embankment (Figure 1) and secondly the site history was modelled to reach a soil stress state and strength profile that matched existing conditions from available ground investigations.

4.2 VALIDATION WITH TRIAL EMBANKMENT STUDY

A trial embankment was constructed in 2011 in close proximity to the project location with the purpose of studying the magnitude and rate of settlement of the Estuarine Clay at Kooragang Island. Monitoring systems including settlement measurement plates (SMP), inclinometers, vibrating wire piezometers (VWP) and extensometers were installed. Monitoring was undertaken for an approximate two year period.

A back-analysis based on interpretation of available monitoring data was carried out in Plaxis 3D to calibrate and validate the Estuarine Clay parameters for the Soft Soil Creep model. A CPT at the centre of the trial embankment provided the subsurface ground stratigraphy adopted in the Plaxis 3D model and initial soil parameters. Available triaxial test results were used to derive the soil strength parameters.

The following parameters of the Estuarine Clay were assessed in this study:

- Compressibility parameters λ^*, κ^* and μ^*; and
- Permeability parameters k and C_k.

In order to simulate the ageing of the estuarine sediments, an initial period of 1100 years consolidation of natural sediments only (particularly the Estuarine Clay), followed by a 40 year consolidation period of the reclamation in the 1960s. As discussed in Chapter 4.1, the approach involved modelling the site history to allow the Soft Soil Creep model to compute the current soil stress state and compare with the OCR from the CPT; hence, the initial ageing phase of the natural sediments. Sensitivity assessment demonstrated that the initial ageing periods beyond 1100 years made negligible difference. The subsequent construction of the trial embankment was modelled based on the embankment geometry, estimated fill loadings (periods and lifts) and available monitoring data.

4.2.1 Compressibility

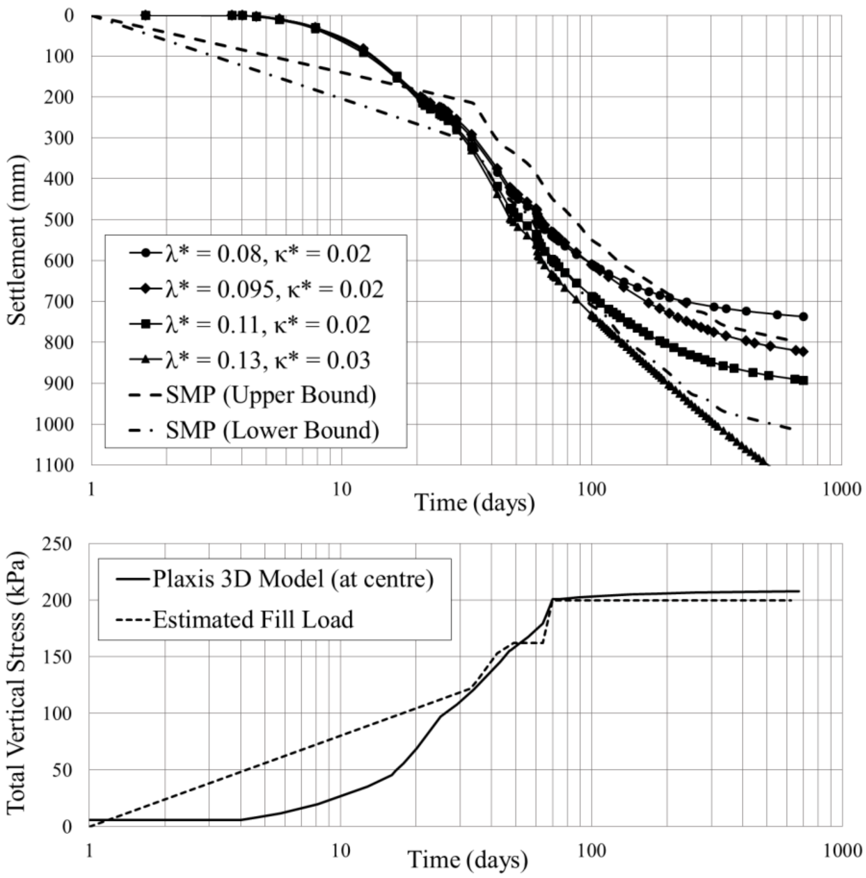


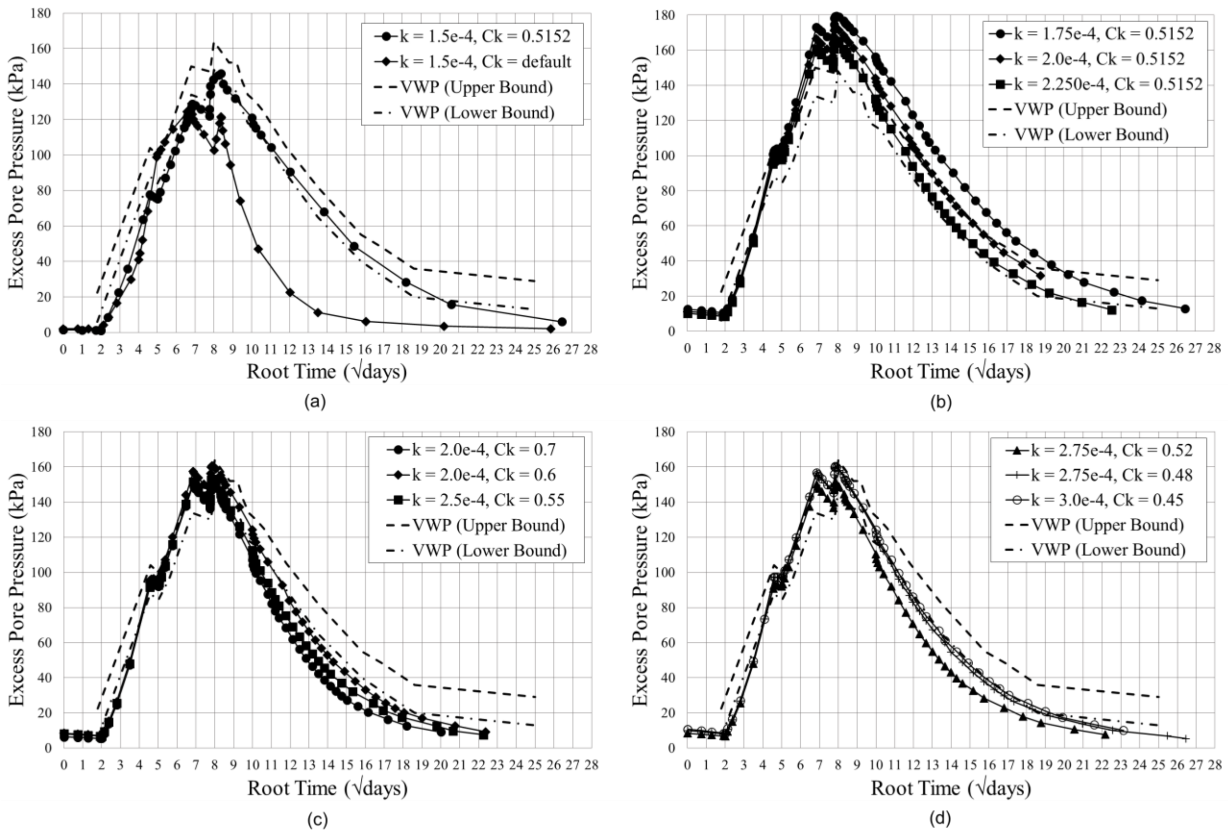
Figure 3: Comparison of overall actual recorded settlements and predicted settlements by Plaxis 3D model with varying compressibility parameters

Compressibility of the Estuarine Clay was investigated in relation to available oedometer tests. All oedometer tests undertaken on the Estuarine Clay samples provide reasonably similar results. The oedometer test results were plotted on a stress-strain curve (void ratio, e, against effective vertical load) in natural logarithm scale. These provided a range of values for C_c, C_s and C_α, which were then adjusted to the modified equivalents λ^*, κ^* and μ^* for input into the Soft Soil Creep model. Note the unload portion of the curve was used for κ^* calculations. A sensitivity analysis was subsequently undertaken on the range of λ^*, κ^* and μ^* values, and the effects on settlement magnitudes are compared in Figure 3. $\lambda^* = 0.095$ to 0.11, $\kappa^* = 0.02$ and $\mu^* = 0.002$ were deemed most appropriate for the Estuarine Clay at Kooragang Island.

4.2.2 Permeability

The permeability of the Estuarine Clay was calibrated against VWPs. The construction staging of the trial embankment was similarly calibrated as above. Initially, it was noted that the magnitude of pore water pressure generated during construction was best matched with a permeability between 1.0×10^{-4} m/day and 3.0×10^{-4} m/day. It was discovered that the rate of dissipation of pore water pressure was too rapid and as such, a change in permeability with compression, C_k, was implemented. At the time when this finding was implemented, $\lambda^* = 0.08$, which is equivalent to $C_c = 0.5152$. Based on the assumption that the change in permeability is approximately equivalent to the change in void ratio, $C_k = C_c = 0.5152$ was adopted with $k = 1.5\text{x}10^{-4}$ m/day. This provides excellent correspondence with VWP measurements as shown in Figure 4a. It should be noted that when using the C_k parameter, recalibration is required if the compressibility of the soil is altered.

In the final iteration of the trial embankment study, $\lambda^* = 0.11$, $\kappa^* = 0.02$ and $\mu^* = 0.002$ were considered to be most appropriate for the Estuarine Clay at Kooragang Island. Adopting these compressibility parameters, Figures 4b, 4c and 4d show the sensitivity of varying permeability parameter k and calibration of C_k with k respectively. Permeability parameters $k = 2.0\text{x}10^{-4}$ m/day to $2.75\text{x}10^{-4}$ m/day and $C_k = 0.45$ to 0.55 were deemed the closest match to the observed data based upon the calibrations performed and hence adopted in the alternative design solution.



(a) (b) (c) (d)

Figure 4: Plots of excess pore pressure of the Estuarine Clay against root time showing: (a) effects of C_k; (b) sensitivity of k; and (c) and (d) calibration of varying k and C_k

5 ALTERNATIVE DESIGN SOLUTION: PRELOADING AND STAGED CONSTRUCTION

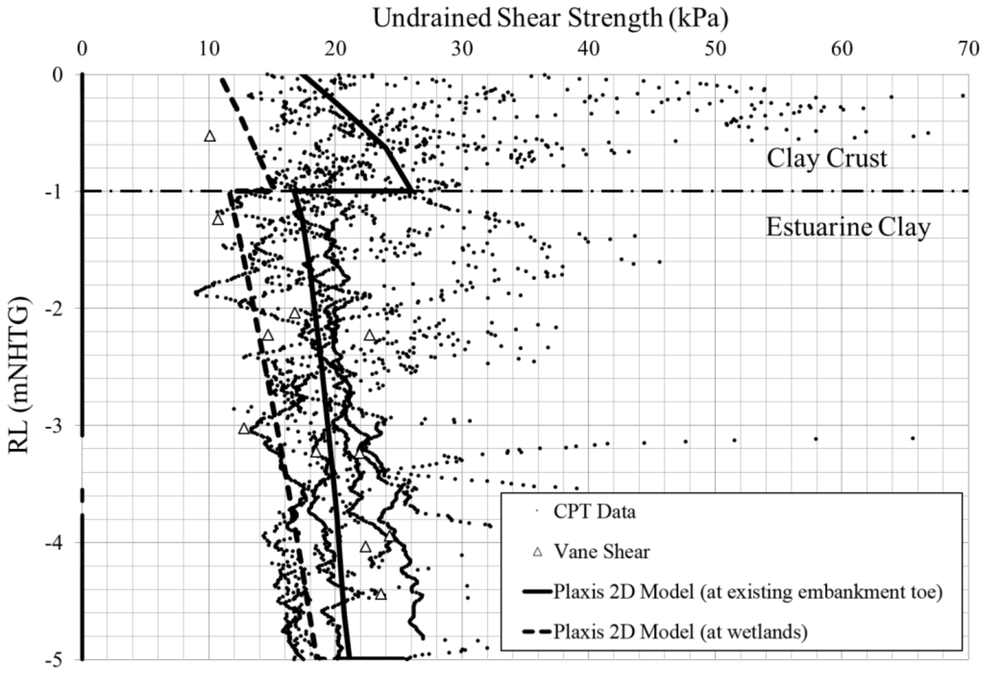


Figure 5: Comparison of undrained shear strength profile of the Estuarine Clay generated by the Soft Soil Creep model against available CPT and vane shear results

The findings of the trial embankment study was next applied to a Plaxis 2D model of the proposed rail embankment design, utilising the Soft Soil Creep model. Similar to the Plaxis 3D model, the site specific history was modelled to develop the current soil stress state. The model was calibrated to match available investigation data of the existing ground. This was achieved by comparing the undrained shear strength and OCR generated by the Plaxis 2D model with available CPT data. Figure 5 demonstrates this undrained shear strength comparison at the wetland side and at the toe of the existing embankment.

With the understanding of the site specific study and the use of the more advanced Soft Soil Creep model, acceptable global stability and settlements were able to be demonstrated with no ground improvement; hence, the alternative design solution (Figure 6). The philosophy of the alternative earthworks design is to undertake preloading and stage the construction to limit post-construction settlements within allowable limits, and implement sufficient instrumentation and monitoring to control the construction and operation of the proposed rail embankment. A gravity retaining structure would then be constructed on the improved ground to support the proposed rail embankment.

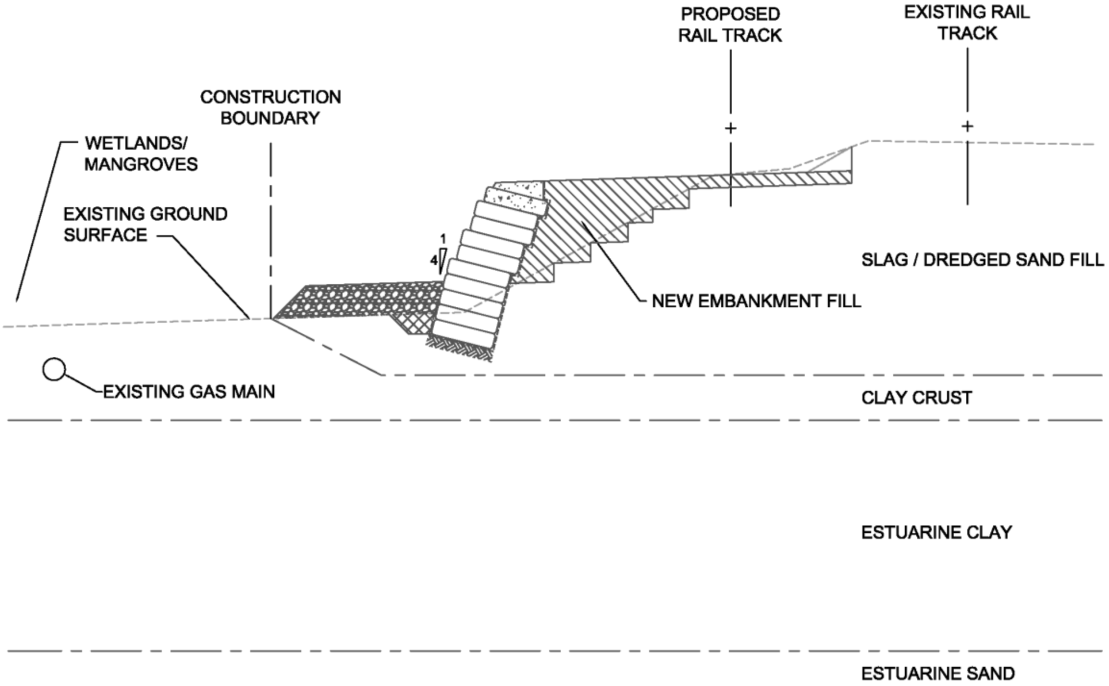


Figure 6: Illustration of revised earthworks design

6 CONCLUSIONS

The design of the Kooragang Coal Terminal (KCT) Arrival Roads has undergone significant geotechnical engineering design development in order to overcome numerous project constraints. It has involved rigorous site specific study and the use of the advanced Soft Soil Creep model to demonstrate a more sensible representation of current site conditions. This realistic design approach not only allowed for improvement of the constructability, but also assured confidence in optimising the rail embankment design without DSM ground improvement, bringing massive potential savings on construction costs. The use of an appropriate advanced constitutive soil model, combined with a rigorous study of site specific data, has proven to reduce conservatism in design and substantially benefit real projects.

This alternative design solution of the KCT Arrival Roads is currently being constructed at the time of writing this paper. The construction of the new rail embankment is closely monitored and valuable data is continually collected from the instrumentation and monitoring regime implemented. Recorded movements are within predicted thus far.

7 ACKNOWLEDGEMENTS

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