

Modelling Behaviour of Soft Estuarine Clay in Newcastle using Soft Soil Creep Model

R. C. Tanuwidjaja¹

¹Arup, Level 10, 201 Kent Street, Sydney, NSW 2000, Australia; PH (+61) 2 9320 9320; FAX (+61) 2 9320 9321; email: renardi.tanuwidjaja@arup.com

ABSTRACT

Soil behaviour is complex, non-linear and very much dependent on its stress state conditions. Advanced constitutive soil models have become more commonly used in an attempt to come closer to simulating realistic soil behaviour. This paper looks at the use of Plaxis Soft Soil Creep model to develop an appropriate representation of the soft Estuarine Clay soil behaviour found at Kooragang Island, Newcastle for the optimisation of 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. Site history and ageing of the Estuarine Clay were 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 ground movements in the past were able to be correlated with available data including CPTs, shear vanes, inclinometer and extensometers. Predictions from the Soft Soil Creep model demonstrate a more sensible representation of current site conditions compared to using basic soil models. This realistic design approach assures confident in optimising the rail embankment design, which brings 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 and substantially benefit real projects.

Keywords: consolidation, soft soil creep, Kooragang Island, Newcastle

1 INTRODUCTION

Soil behaviour is very much complex and often difficult to predict. It is common 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 analysis, there are situations where this is not possible due to project specific constraints. 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, overcoming project constraints and reducing 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. At the location of this case study, there are currently two existing rail tracks 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, withstanding the 1989 Newcastle earthquake.

Several constraints complicate the construction of the proposed rail embankment. These include:

- Presence of very soft to soft Estuarine Clay, which may cause excessive settlements beyond rail operation tolerances and trigger a global slope instability shearing through this soft layer;
- Existing high pressure gas pipeline runs parallel along the existing rail embankment, limiting construction area and allowable stress/deformation effects on the pipeline;
- 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 in the wetlands area;
- Low lying swamp bounded by the existing reclamation and rail infrastructure;
- Natural watercourses and creeks; 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. Industrial development in the 1960's led to dredged sand fill reclamation, which amalgamated the former islands into the current larger Kooragang Island. The project site area – refer Figure 1(a) – 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.

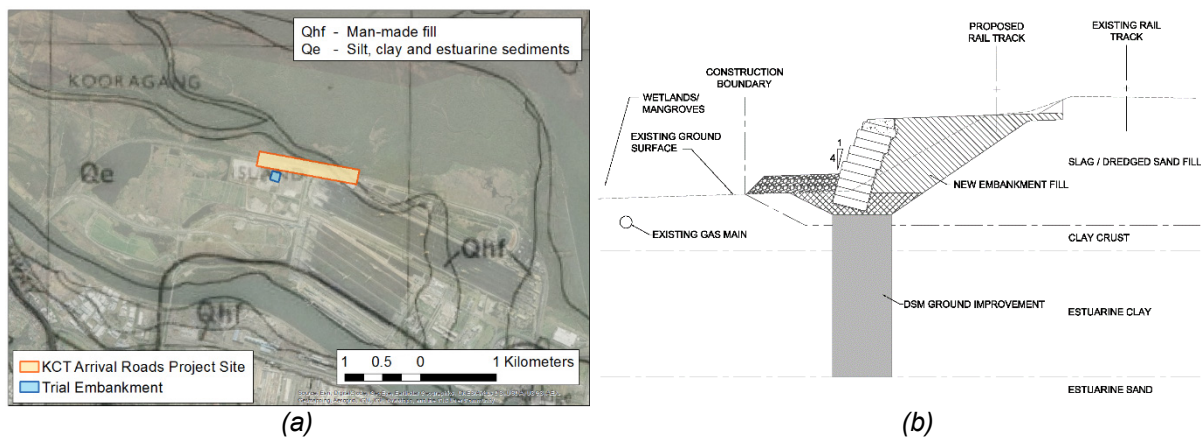


Figure 1. (a) Project site location and geology; (b) Illustration of original ground improvement design

A series of ground investigations have been undertaken at the project site, including 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, known to be up to 14 m thick at the old paleo-channel. 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 considerable consolidation under the existing rail embankment and live heavy rail loads.

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 dry soil mix technique to improve shear strength and limit compressibility of the Estuarine Clay under the proposed embankment extension, as illustrated in Figure 1(b). A gravity retaining structure constructed on the improved ground will support the proposed rail embankment. The ground improvement would: 1) provide a suitable foundation for the proposed retaining structure and proposed rail embankment extension; 2) achieve acceptable ground deformations and embankment stability; and 3) limit the impacts of the proposed embankment on the existing gas pipeline. Ground improvement would normally have been appropriate, as have been previously utilised on Kooragang Island including the Newcastle Coal Infrastructure Group (NCIG) projects (Hawkins et al., 2008 and Chua et al., 2008). However, the constraints discussed in Chapter 1 limit the constructability of the original ground improvement scheme and another design solution had to be put forward.

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.

This modelling approach relies on available CPTs and in-situ shear vanes to determine the undrained shear strength parameter of the soft Estuarine Clay. However, these tests were restricted to locations

at the wetlands or near the toe of the existing embankment. The Estuarine Clay immediately beneath the existing embankment is expected to have higher shear strengths due to consolidation over time from the rail and embankment surcharge, decreasing further away from the embankment toe. The simple slope model was not able to utilise this strength gain to accurately capture this gradient shear strength profile due to limitations of available testing and soil model applied. The 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).

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, similar to 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 dependent on the permeability (k) and change of permeability (C_k) of the material, as further discussed in Chapter 4.2.2.

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

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

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

$$\log(k / k_0) = \Delta e / C_k \quad (4)$$

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(a) – 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, as shown in Figure 1(a), 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. Compressibility parameters (λ^* , κ^* and μ^*) and permeability parameters (k and C_k) of the Estuarine Clay were assessed in this study. Initial parameters used in the model were derived from available laboratory and in-situ test results.

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 were modelled in Plaxis 3D. 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. The Estuarine Clay parameters were then adjusted to

match with monitoring results of the trial embankment. The set of parameters demonstrating sensible results in the Plaxis 3D model of the trial embankment were then adopted in the Plaxis 2D model for the alternative design solution.

4.2.1 Compressibility

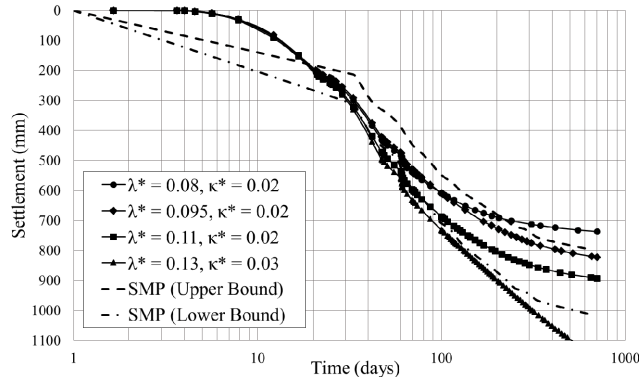


Figure 2. Comparison of overall actual recorded settlements and predicted settlements by Plaxis 3D model with varying compressibility parameters

Compressibility of the Estuarine Clay was investigated in relation to available oedometer tests. The oedometer tests undertaken on the Estuarine Clay samples provide reasonably similar results. All oedometer 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 are compared in Figure 2. $\lambda^* = 0.095$ 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

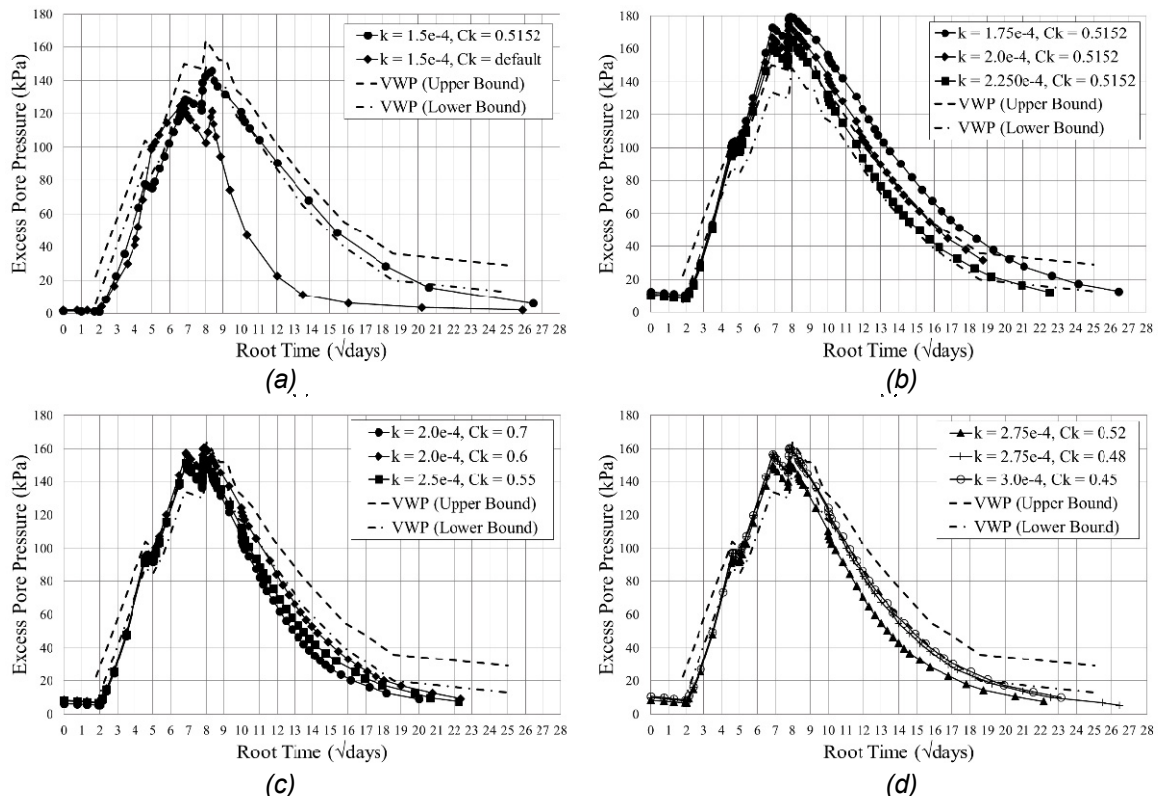


Figure 3. Plots of excess pore pressure of the Estuarine Clay against root time showing: (a) effects of C_k ; (b) sensitivity of k ; and (c) and (d) calibration of varying k and C_k

The permeability of the Estuarine Clay was calibrated against VWP. 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 corresponded with 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. 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 initially adopted with $k = 1.5 \times 10^{-4}$ m/day. This provides excellent correlation with VWP measurements as shown in Figure 3(a). 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. Figures 3(b), 3(c) and 3(d) show the sensitivity of varying permeability parameter k and calibration of C_k with k respectively. Permeability parameters $k = 2.0 \times 10^{-4}$ m/day to 2.75×10^{-4} m/day and $C_k = 0.45$ to 0.55 were deemed appropriate and hence adopted in the alternative design solution.

5 ALTERNATIVE DESIGN SOLUTION: PRELOADING AND STAGED CONSTRUCTION

The Soft Soil Creep parameters of the Estuarine Clay validated by the trial embankment study were then applied to a Plaxis 2D model of the proposed rail embankment design. Similar to the Plaxis 3D model, the site specific history was modelled to develop the current soil stress state. That is, the ageing of the Estuarine Clay was first modelled, followed by the reclamation and construction of the existing rail embankment approximately 40 years ago. At this stage, prior to further modelling the construction stages of the proposed rail embankment design, the resulting undrained shear strength profile (Figure 4(a)) and OCR were assessed with available investigation of the existing ground. The undrained shear strength is compared with CPT and hand shear vane tests that are available at the wetland side and at the toe of the existing embankment, as displayed in Figure 4(b). Calculated settlements over the last 40 years and FOS of the existing embankment were also assessed by comparing with field observations. The results of modelling the site history generally agrees with available data and field observations. This further validates the reliability and accuracy of the model, in particular the Estuarine Clay parameters used in the Soft Soil Creep model. The construction phases of the alternative design solution is subsequently modelled to assess its acceptability.

As discussed in Chapter 3.2, relying on only the limited CPTs and hand shear vane tests available towards the wetlands side is likely conservative. Figure 4(a) demonstrates how the Soft Soil Creep model has taken advantage of the expected strength gain in the Estuarine Clay immediately beneath the existing rail embankment from consolidation and creep over time.

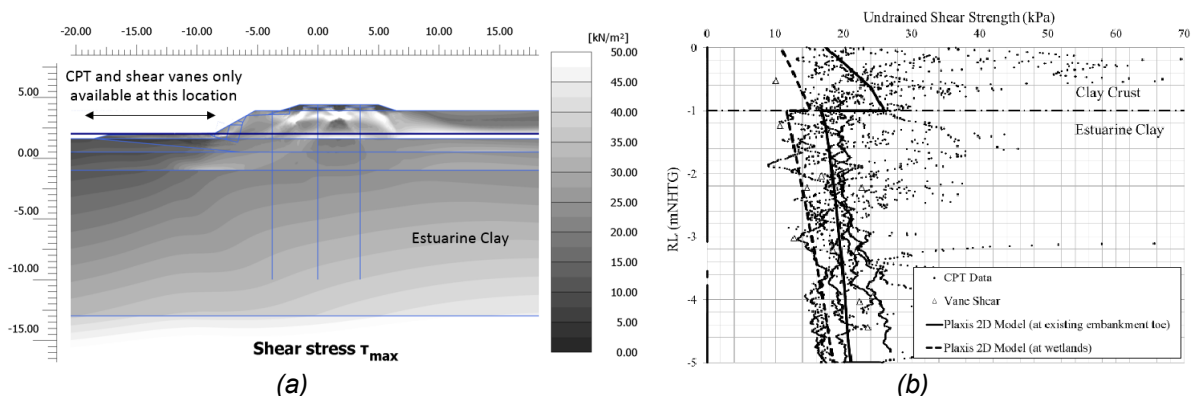


Figure 4. (a) Calculated undrained shear strength profile of current site condition after site history phases modelled in Plaxis 2D; (b) Comparison of undrained shear strength profile of the Estuarine Clay generated by the Soft Soil Creep model against available CPT and vane shear results

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 5). 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.

Caution should be exercised when using the Soft Soil Creep model. The results of using the Soft Soil Creep model is very much sensitive to the input parameters and construction phases developed in Plaxis. In the case of KCT Arrival Roads, the combination of a sound knowledge of the site history, available in-situ and laboratory tests, and trial embankment monitoring contributed to validating the reliability and accuracy of using the Soft Soil Creep model.

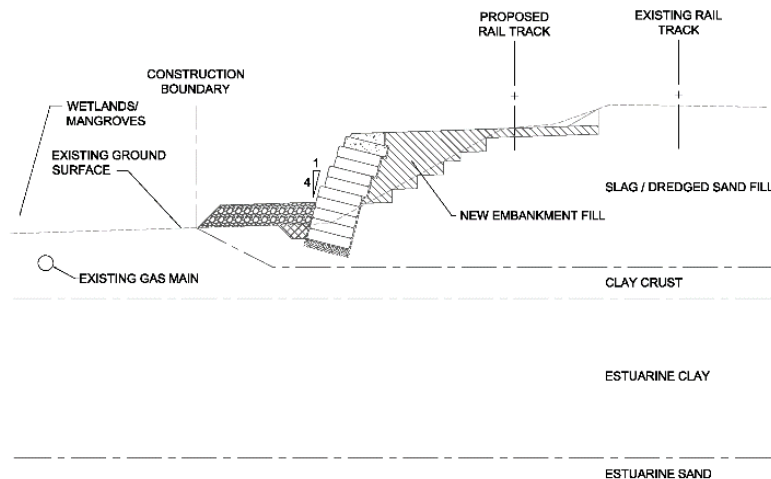


Figure 5. Illustration of revised earthworks design

6 CONCLUSION

The design of the 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 assures confidence in optimising the rail embankment design without DSM ground improvement, bringing massive potential savings on construction costs on this project.

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

The author would like to express his gratitude to Greg Cavanagh, David Buttenshaw, Aaron Manderson and the Australian Rail Track Corporation for their kind permission to publish this paper. Much appreciation is given to Sergei Terzaghi and Karen Oj, whom without their knowledge and guidance, the design of KCT Arrival Roads and this paper would not have been possible. Lastly, a special thanks is given to Hui Ling Lim for her encouragement and review of this paper.

REFERENCES

- Chua, C. C. H., Lai, M., Hoffmann, G. and Hawkins, B. (2008). "Ground Improvement using Dynamic Replacement for NCIG CET3 Coal Stockyard", *Australian Geomechanics*, 43(3), pp. 63-74
- Fityus, S., Hawkins, G., Delaney, M. and Morton, S. (2005). "An overview of engineering geology and geotechnical challenges in the Newcastle Region", *Australian Geomechanics*, 40(1), pp. 5-28.
- Hawkins, B., Chua, C. C. H. and Niu, J. (2008). "NCIG CET3 Project", *Australian Geomechanics*, 43(3), pp. 53-62.
- McCue, K. F., Wesson, V. and Gibson, G. M. (1990). "The Newcastle, New South Wales, earthquake of 28 December 1989." Bureau of Mineral Resources, *Journal of Australian Geology and Geophysics*, 11, pp. 559-567.
- Terzaghi, K. and Peck, R. B. (1967). *Soil mechanics in engineering practice*, 2nd Edition, John Wiley and Sons, New York.
- Waterman, D. and Broere, W. (2004). *Practical Application of Soft Soil Creep Model*, Plaxis.
- Waterman, D. and Broere, W. (2004). *Practical Application of Soft Soil Creep Model Part II: Undrained Behaviour*, Plaxis.
- Waterman, D. and Broere, W. (2005). *Practical Application of Soft Soil Creep Model Part III: Parameter Determination*, Plaxis.