Verification of consolidation parameters of a near-normally consolidated clay by back-analysis of an instrumented, wick-drained reclamation

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ABSTRACT

Reclamation of an estuarine waterway on 20m of near-normally consolidated clay was required to have less than 0.3m of residual settlement after 3years, compared with predicted settlement of 3m. To address this, wick drains and staged preloading was adopted. Popular belief is that the clay contains sand laminations and other structure which result in anisotropy of permeability at small scales, and shorter drainage paths than the full layer thickness on the macro scale. However, performance of a previous reclamation under similar conditions suggested the marine clay may act as a single isotropic layer, and the reclamation was designed on this basis. The reclamation was instrumented to measure settlements and excess pore pressures, and the observed settlement over 3.5 years closely matched the best estimates of predicted settlement. Subsequent back-analysis using finite difference modelling techniques suggests that the clay has near-isotropic permeability over scales of several metres, but in at least some areas there are beds of material several metres thick with permeability variations of greater than an order of magnitude. Additionally, the apparent permeability of the clay was found to significantly reduce with time, possibly due to clogging of drainage paths within the clay and wick drains.

1 PROJECT DESCRIPTION

As part of the Victoria Dock Redevelopment Project, in the Port of Melbourne, Victoria, Australia, the Mouth of Moonee Ponds Creek was required to be diverted, and the original creek bed reclaimed to provide a land area for a proposed container park. The reclamation was placed over deep deposits of very soft Mud and soft to firm Coode Island Silt (CIS) which undergo large, slow consolidation settlements under surcharge loads. The design of the works adopted a target settlement of not more than 0.3m over the 20years following removal of the surcharge under the combined loads from fill, pavements and container loads. An idealised section through the reclamation is shown as Figure 1.

For the average (or "best") estimate of predicted settlement to achieve the settlement criteria, the central section of the reclamation in the creek bed was loaded with up to 11m of fill and surcharge wick drains installed to the base of the CIS. It was anticipated that this area would undergo settlements of up to 3m with a large proportion of this settlement occurring over the first 3 years. The banks of the creek, were loaded with up to 6m of fill and surcharge without wick drains. Smaller settlements, typically around 1 to 1.5m were anticipated for these areas, but it was expected that it would typically take more than 30 years for all of this settlement to occur.

The very low shear strength of the soils, and the Mud in particular, meant that stability of the reclamation was a major issue for construction. To deal with this high strength geofabric was used as a basal reinforcement in the creek bed, and fill placement was staged over a 12 month period to allow progressive strength gain of the foundation soils prior to the full surcharge load being applied.

Extensive monitoring of settlements and pore pressures was undertaken to confirm compliance with the design intent. The results from this monitoring have been back analysed by finite difference methods to provide quite an accurate assessment of the consolidation properties of the foundation soils, which can be compared with the predicted properties and settlements.

The CIS is underlain by Fisherman's Bend Silt (FBS). Although this material is overconsolidated, it was expected to undergo some consolidation under the design loads, and also influence the drainage path for consolidation of the CIS. These effects were addressed by both the design and back-analysis, but space does not permit discussion of the FBS in this paper. For the purpose of this paper, the FBS can be considered to approximate a rigid, free draining base.

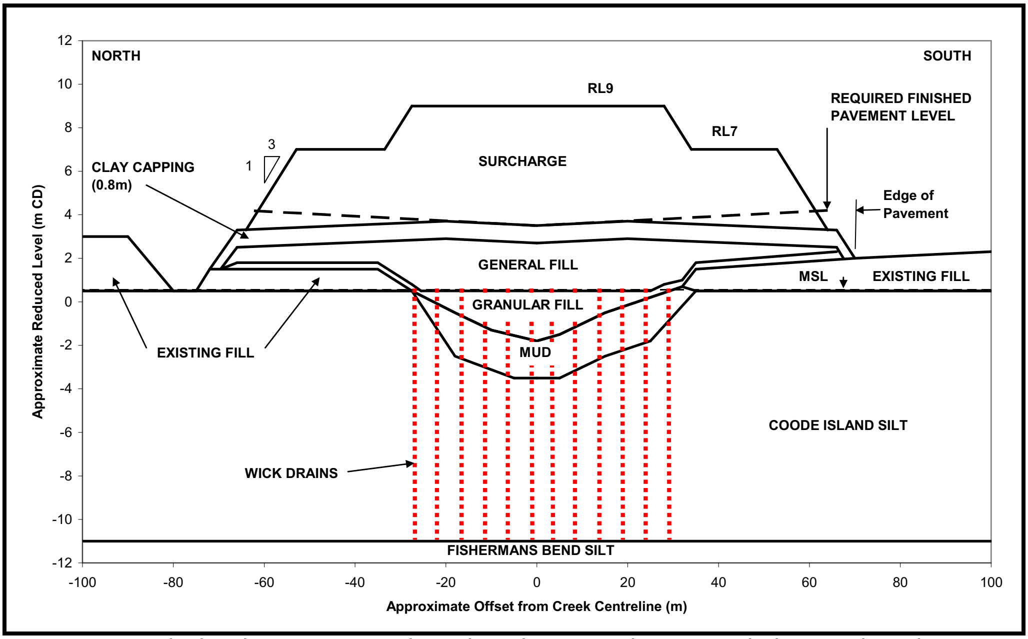

Figure 1: Idealised cross-section through reclamation showing wick drain and surcharge

2 PREDICTED CONSOLIDATION PROPERTIES AND SETTLEMENT

Coode Island Silt (CIS) is a Quarternary deposit, which predominantly comprises slightly over-consolidated, high plasticity clay. In the early stage of the project it was hypothesised that the Mud was just the surficial layer of the CIS. However, in the course of the project it was established that in the early 1900's, Moonee Ponds Creek had been dredged to form the Coal Canal. The Mud therefore appears to be under-consolidated material deposited in the dredged channel over the last century. Nevertheless, the visual descriptions and plasticity results for the CIS and Mud were very similar. More significantly, consolidation tests on the Mud and CIS gave very similar compression and recompression indices and consolidation curves converged to a similar void ratio in the normally consolidated range (see Figure 2). The results suggest that the Mud and CIS were generated from similar materials and deposition processes, albeit of a different age.

As well as the differing pre-consolidation pressure, a second important distinction between the Mud and the CIS is the rate of consolidation as indicated by the vertical coefficient of consolidation (c_v). At low confining pressures c_v of the mud was calculated as approximately 10 times that of the CIS. This is to be expected as the mud has a higher void ratio than the CIS and hence higher permeability. At high confining pressures, where both the Mud and CIS had similar void ratio, both had a similar value of c_v.

While the c_v of the Mud reduced with increasing confining pressure, the c_v of the CIS remained roughly constant with increasing confining pressure. The drained stiffness of the CIS was also observed to increase approximately directly proportionally to the confining pressure for the range of insitu stresses applicable to the project. The coefficient of volume change (m_v) is the inverse of the drained stiffness and is related to permeability (k) and coefficient of consolidation by Equation 1, where γ_w is the bulk unit weight of water.

$$k = c_v.\gamma_w.m_v \qquad (1)$$

The linear increase in stiffness with depth and roughly constant c_v therefore implies a the permeability of the CIS is approximately inversely proportional to the confining pressure.

As well as the laboratory consolidation tests, insitu piezocone dissipation tests were carried out. The radial coefficient of consolidation (c_r) calculated from these tests was consistently around 10 times higher than the corresponding c_v in all of the materials tested (Mud, CIS and FBS). A common belief in Melbourne is that fine sand laminations within the structure of the CIS lead to a significantly higher soil permeability in the horizontal direction than in the vertical direction. The piezocone dissipation tests tend to support this belief. However, the first author has previously been associated with a project where a wick drained embankment in CIS was back-analysed to have an anisotropy ratio (c_r/c_v) of between 1 and 2. On the weight of this previous experience, the predictions of settlements with wick drains present were based on an anisotropy ratio of 1.

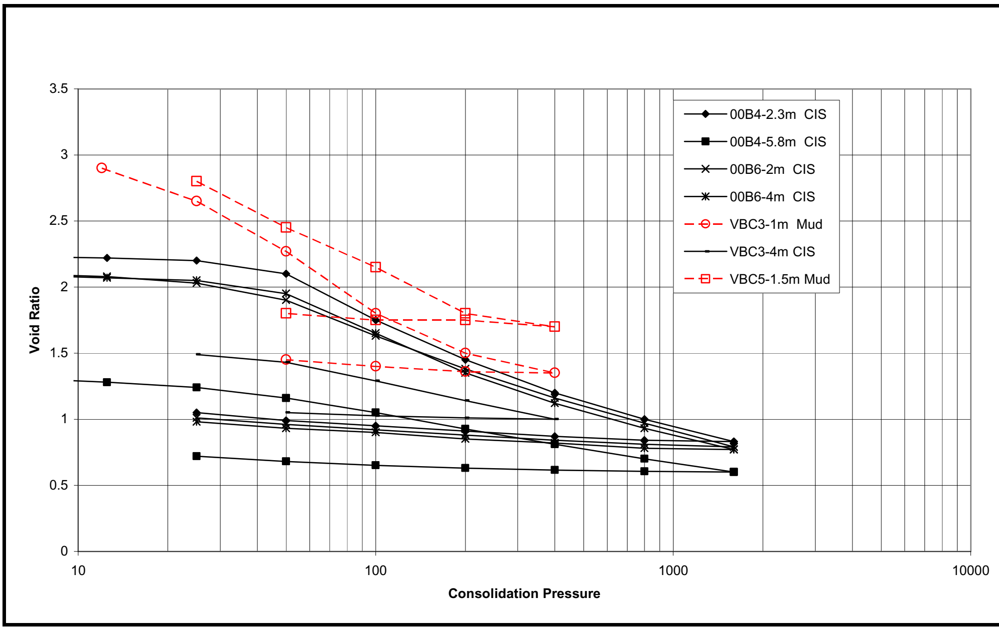

Figure 2: Consolidation Curves for CIS and Mud

Table 1: Rearranged parameters used for prediction of settlements

Design Parameter	**Mud**	**CIS in creek**	**CIS on land**
Specific Gravity of Solids (sg)	2.6		
Compression Index (Cc)	0.9		
Recompression Index (Cr)	0.05		
Void ratio at 1kPa vertical pressure extrapolated from Cc (e_1)	3.25		
Vertical coefficient of consolidation (and likely range) (c_v)	$3m^2/y$ (1 to 10)	$0.4m^2/y$ (0.2 to 1.0)	
Average vertical permeability (and likely range) (k_v)	0.06m/y (0.02 to 0.2)	0.005m/y (0.002 to 0.015)	
Ratio radial to vertical permeability (c_r/c_v or k_r/k_v)	no wick drains = 3 to 5 with wick drains = 1		
Overconsolidation ($ocp=p'_c-p'_o$)	1kPa	25kPa	15kPa
Secondary consolidation coefficient on log cycle of time (c_α)	2%	1.5% (but not less than 10mm/year total)	

The predictions of settlement were based on conventional "degree of consolidation" charts using dimensionless time factors. To take into account the effect of combined vertical and horizontal flow, superposition of radial consolidation from wicks and vertical consolidation through a layered soil was used. The parameters used in the calculations have been re-arranged to facilitate finite difference calculations and are summarised in the form shown in Table 1. Note that for ease of computation the permeability in Table 1 is calculated from Equation 1 as an average through the layer based on the value of m_v calculated at the centre of the layer using the maximum surcharge increment.

The assumed staging of construction and the resulting prediction of the range of settlement versus time in the centre of the creek, with wick drains and surcharge is shown as Figure 3.

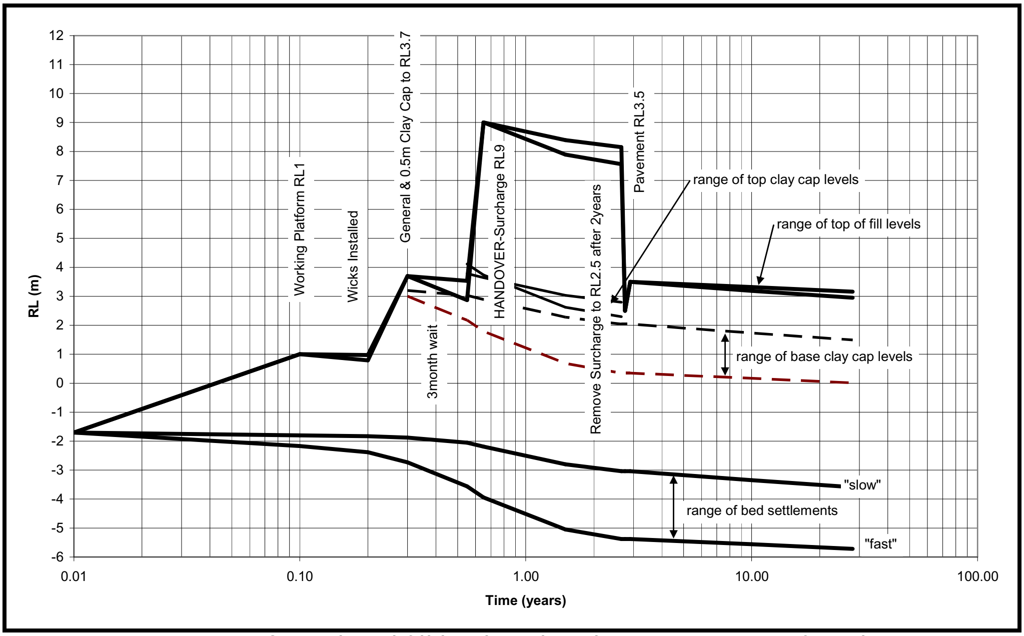

Figure 3: Predicted fill levels and settlements in centre of creek

3 MEASURED SETTLEMENTS

Monitoring data was collected over a period of 3.5 years. The results were grouped into areas with similar geometry and stratigraphy. Space does not permit inclusion of all the monitoring results, but Figure 4 shows surface settlements and piezometer readings in the CIS at the centre of the creek. The settlements in the first year show some deviations from "best" estimate predictions in the first year due to the rate of filling not being the same as assumed, but taking this into account the results closely match predictions. By contrast, in the last year of the records, the rate of settlements has slowed compared with predictions, and excess pore pressures are relatively high in some instances. It is important to note that the surcharge had still not been removed at the time of the last monitoring results, and hence the reduction in settlement rates predicted at 2.5 years should not yet have occurred.

It is important to note that the reclamation included areas with and without wick drains, with and without mud, and with varying levels of surcharge. In all there were six different sets of data covering differing scenarios. All of this data was able to be cross correlated to identify the effects of different parameters on the predictions. For the most part, the observations gave reasonably good agreement with the "best" estimate predictions, but there were noticeable discrepancies with respect to excess pore pressures in some of the records, and in most cases the rates of settlement have started to slow relative to predictions.

4 BACK-ANALYSIS

The calculation method used for the predictions shown in Figure 3 was based on average degree of consolidation, and therefore does not give any detailed predictions of excess pore pressures. To allow a back-analysis that considers rate of application of surcharge, and combined vertical and radial drainage in a layered soil, a finite difference analysis spreadsheet was developed.

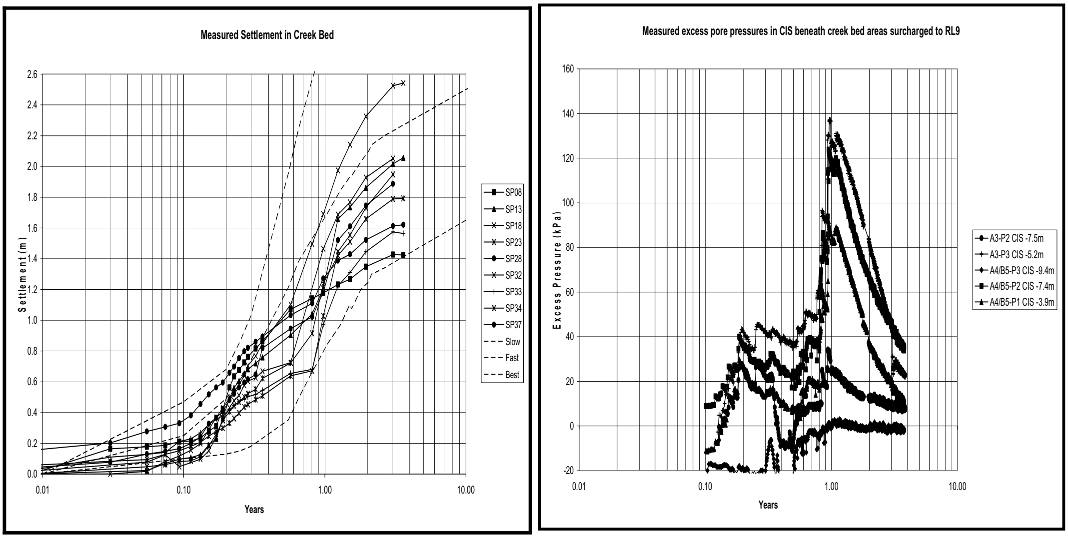

Figure 4: Settlement and piezometer monitoring in centre of creek under maximum surcharge

The spreadsheet was originally set up to calculate a coefficient of volume change (m_v) and average permeability (k) based on the maximum surcharge increment. Although the applied surcharge varied with time, these values were kept constant throughout the analysis. This is a technique common to most consolidation analyses, and was not seen as a significant limitation of the spreadsheet at the time, particularly given that the c_v of the CIS remained fairly constant for a range of applied surcharge.

In the course of the back analysis it became apparent that the permeability of the ground was changing with time, and a facility to introduce a linear variation in permeability with respect to time was therefore introduced. Ideally, a consolidation model which took into account the relationship between current void ratio, current coefficient of volume change and current permeability would be desirable. However, it needs to be recognised that the laboratory consolidation tests do not directly yield this information.

Based on the back-analysis of the monitoring data, for the most part, the parameters adopted in the prediction of settlements as given in Table 1 appear to be accurate. The exceptions and refinements that came out of the analysis were as follows:

- The overconsolidation of the CIS was calculated at between 10 and 25kPa, but there did not appear to be a clear correlation between preconsolidation and location.

- Average vertical permeability (kv) of both Mud and CIS was calculated as initially 0.03m/year to match the early part of the record. However there is strong evidence to suggest that the permeability of Mud and CIS varies both with location and time. There was not a unique relationship for permeability that could be inferred from the data that could be used for all locations. On balance a reduction in permeability with time seems to give the best overall match to the record, but layers of CIS with differing permeability is the only reasonable explanation for the observed piezometer data at one location.

- There is some evidence to suggest that the radial permeability of the CIS is up to twice the vertical permeability, but it also appears to reduce with time more dramatically than the vertical permeability. For practical purposes the permeability of the CIS could be considered isotropic (i.e. kr/kv=1).

- Assuming isotropic permeability of the CIS, on average, an initial permeability of 0.05m/year reducing to 0.005m/year by the end of the first year would give an approximate match between predicted and actual settlements. However, this could under or over-estimate the magnitude of settlement significantly beyond 3 to 4 years.

- The monitoring data was unable to establish rates of secondary consolidation. Historical records for the CIS though South Melbourne and Port Melbourne in general suggest secondary consolidation rates of 5 to 10mm per year continuing for many years.

Using the above parameters it was determined that after 3.5 years (the last set of monitoring data), the parts of the reclamation where wick drains were installed was at about 95% primary consolidation for the current level of surcharge.

On the creek banks where no wick drains were installed it was estimated that an average of 65% of the total primary consolidation under the current levels of surcharge had occurred, and that it would take approximately another 20 years for 95% of primary consolidation to occur if there were no changes in fill levels.

5 CONCLUSIONS

The results of back-analysis of the reclamation indicate that, at least at the location of Moonee Ponds Creek, Coode Island Silt is predominantly a single isotropic layer with consolidation properties similar to those determined from laboratory consolidation tests. In this context settlement predictions based on a commonly adopted assumption of significantly higher permeability in the horizontal direction would greatly over-estimate rates of settlement for wick-drained embankments.

Although most of the site appeared isotropic, there was evidence of a sub-layer several metres thick within the Coode Island Silt with a permeability greater than an order of magnitude higher in one part of the site. In this area the response was anisotropic, hence the assumption of isotropy cannot necessarily be extrapolated to other sites.

There was also evidence of variations in the level of preconsolidation in the Coode Island Silt occurring over relatively short distances that could not necessarily be directly related to the past fill levels.

Additionally, the apparent permeability of the clay was found to significantly reduce with time, to an extent greater than would be explained by consolidation of the soil alone. Possibly there is some clogging of drainage paths occurring within the clay and wick drains. However the mechanism by which this reduction in permeability occurs can only be hypothesised at this point and further investigation into the causes is warranted.

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REFERENCES

Nil