Some Experiences with Performance Monitoring of Embankments on Soft Clays

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Summary Three trial earth embankments founded on soft sensitive marine clays constructed along the eastern coast belt have been investigated. Soft sensitive clays pose significant challenges to control of stability during construction in not providing adequate warning prior to failure due to their brittle nature. The findings from the trial embankments have confirmed that reliance on lateral movements to control stability would not be prudent and rate of pore pressure build up with embankment load might be a better indicator of the onset of yielding and impending instability. The effectiveness of ground improvement schemes such as wick drains and stone columns in sensitive soft clays which require excavating holes in the soft clay for inclusion of these elements has been investigated. Installation of these elements appears to cause more disturbance to the soil fabric and hence their effectiveness has been shown to be significantly impaired in these sensitive clays.

1. INTRODUCTION

For more than two decades, the Geotechnical Group at Main Roads have been involved in major road projects along the eastern coast-belt. These road alignments have traversed through virtually every coastal plain landform; for example, mudflats, swamps, etc typical of holocene deposits. These road projects have been subjected to extensive geotechnical investigations comprising more recent tools both in the laboratory and in the field (eg, stress path triaxial testing, piezocone). The design philosophies have always included field instrumentation and in selected projects have had the advantage of instrumented trial embankments.

This paper presents some results from three instrumented trial embankments (constructed with conventional earthworks) from the Gold Coast, the Sunshine Coast and Mackay. Previous publications, Robertson & Reeves (1980) and Litwinowicz, Wijeyakulasuriya and Brandon (1994) have addressed selected aspects from the Mackay and Sunshine Coast trial embankments respectively. This paper attempts to establish a common framework for the understanding of these clays which all possess high liquidity indices [LI = (natural moisture – plastic limit) / plasticity index] and display sensitive behaviour. The influence of sensitive behaviour on construction control of stability and effectiveness of ground improvement schemes (eg, wick drains and stone columns) is also investigated.

2. TYPICAL GEOTECHNICAL CHARACTERISTICS

The undrained shear strength of these soft/very soft estuarine silty clays based on the field shear vane is around 10-15 kPa displaying natural moisture contents generally between 60% and 120%. The liquidity indices are generally in the range of 1.5 – 2.5 displaying high sensitivity. Compressibilities as high as $C_c/(1 + e_o) = 0.4 - 0.5$ have been observed in the laboratory. At these high compressibilities, strain rate effects can be significant (Kabbaj et al 1988 and Leroueil (1996)). Macro fabric features (eg, sand lenses) have been variable and in the worst cases $C_v/C_h = 1.0$ and $C_v = 0.1 - 0.3$ m^2/yr have been typical based on laboratory testing. With organic contents up to 10%, high creep rates ($C_{\alpha\varepsilon} > 1\%$) have been observed. Given the sensitivity of the soft clays, the compressibility parameters are likely to be underestimated in the normally consolidated range. Piezocone dissipation tests are also masked by the remoulding of the clay caused by insertion of the cone.

3. ROLE OF INSTRUMENTED EMBANKMENTS

A sound design philosophy for embankments on soft clays should incorporate the use of an observational approach. Such approach is required because of uncertainties associated with the ground conditions, design parameters, and calculation methods. An observational approach which is based on performance monitoring is generally undertaken at Main Roads to address the following issues; namely,

- construction control of stability

- determination of progress of consolidation; eg, for commencement of piling
- refined prediction of in-service settlements for maintenance management
- input to assessment of fill quantities and associated contractual resolutions
- assessment of construction techniques, ground improvement schemes and pavement configurations via trial embankments.

The trial embankments reported in this paper were undertaken primarily to address the following aims:

➢ Case Study A: Trial embankment at Mackay (1977): the viability of a stage constructed approach to achieve embankment heights typically 5 m on soft compressible clays with macro drainage features. The construction period was 6 months with a preload period of 9 months.

➢ Case Study B: Trial embankment at Sunshine Motorway (1992): to assess the feasibility of 2-staged construction in an overall construction period of 300 days, with an initial crest height of 2.6 m to be built in the first lift; in-situ compressibility and consolidation characteristics; and the effectiveness of wick drains for settlement acceleration.

➢ Case Study C: Trial embankment at Coombabah Creek (Gold Coast) (1995): to assess in-situ compressibility and consolidation characteristics of the soft clays and the effectiveness of stone columns for both settlement reduction and acceleration.

Geotechnical characterisation of the sites undertaken as part of the comprehensive geotechnical investigations had in turn facilitated the planning of the instrument locations. The trial embankments have been instrumented with piezometers, inclinometers, settlement gauges, extensometers and horizontal profile gauges along with specialized instrumentation where high strength geosynthetic reinforcement (case study B) and stone columns (case study C) were involved.

4. CASE STUDY A: TRIAL EMBANKMENT AT MACKAY

The southern approaches to the Ron Camm Bridge required embankment heights typically 5 m founded on compressible estuarine muds up to 9 m thickness. Geotechnical investigations had identified macro fabric features (sand lenses/bands). The trial embankment consisted of a rectangular embankment, 100 m by 60 m at the base, with maximum 1 on 3 batters. The trial embankment height was 4.1 m with a further 0.4 m added after a 6 week break.

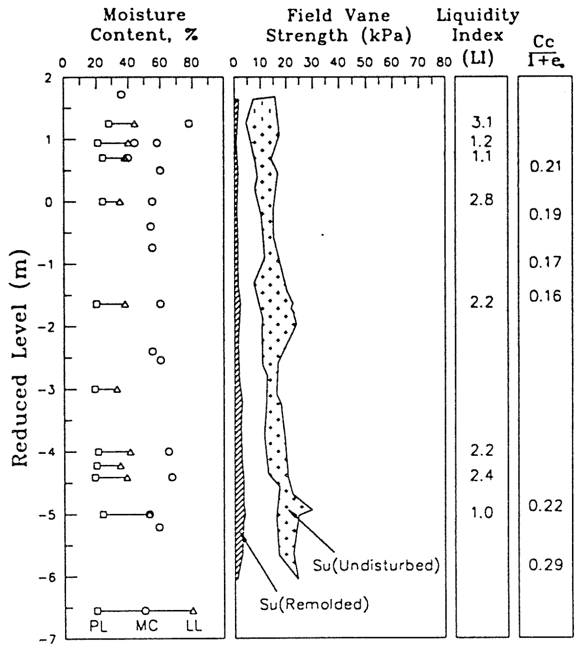

Figure 1. Geotechnical properties (Case A)

The moisture/plasticity and undrained strength characteristics are shown in Fig. 1. The high LI values are noted. The sensitivity of undrained strength based on the field shear vane is between 5 and 30 with an average of 15.

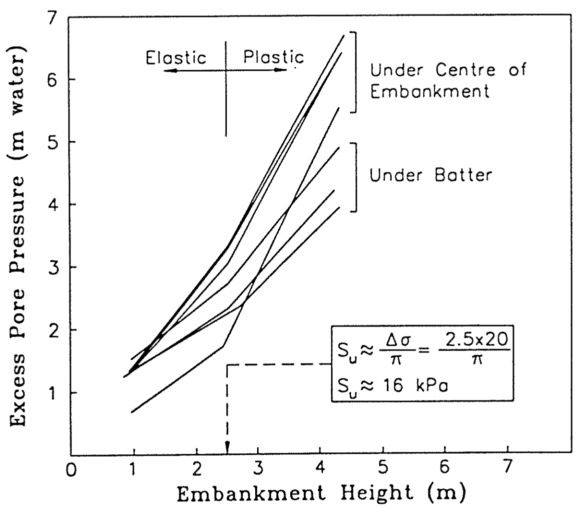

Figure 2. Relation between pore pressure and vertical total stress (Case A)

Figure 2 shows yielding of the soft clay has taken place during construction (change in pore pressure response) and the soft clay has become normally consolidated (NC). With the passage of the clay to the NC state, one would expect the drainage rates to reduce drastically causing undrained behaviour. This should have manifested in high lateral/vertical displacement ratios (on the average around 0.91 according to Tavenas et al (1979)). However, the observed ratio was 0.25, Fig. 3.

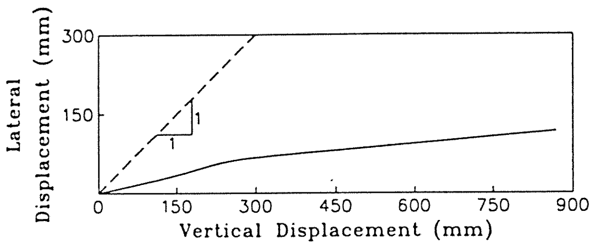

Figure 3. Variation in lateral displacement with settlement (Case A)

As shown in Fig. 2, the applied embankment loading, at the abrupt change in pore pressure response, indicative of the onset of plastic straining, can be used to backfigure an approximate value for the undrained shear strength, S_u of the clay.

5. CASE STUDY B: TRIAL EMBANKMENT AT SUNSHINE MOTORWAY

This section of the motorway traverses a swamp comprising very soft/soft organic marine silty clay ranging in thickness from 4-10 m underlain by sandy deposits, Fig. 4.

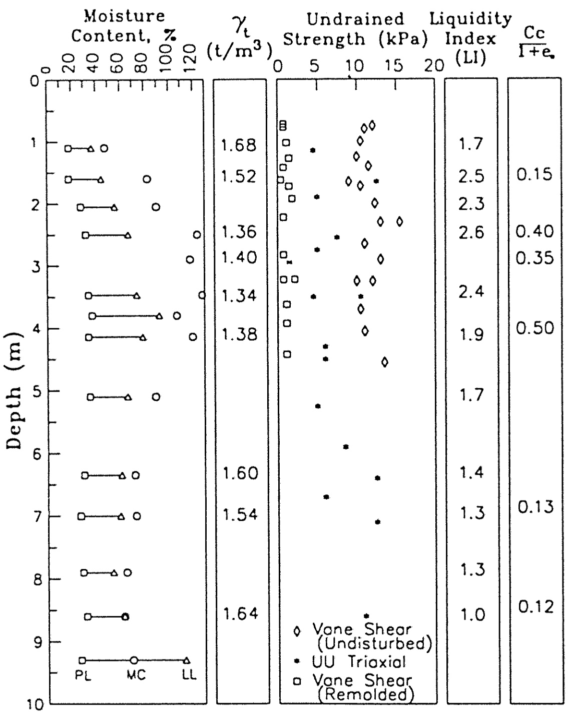

Figure 4. Geotechnical properties (Case B)

The high LI values up to 2.6 are noted within the middle layer. The sensitivity of undrained strength based on the field shear vane is between 4 and 18 with an average of 10. Sampling disturbances tend to consistently underestimate the triaxial UU strengths with respect to field shear vane strengths.

The total thickness of the trial embankment which was reinforced with a high strength geosynthetic at the embankment/foundation interface was 2.8 m. The trial embankment had a top width of 17 m on nominally 1V:2H batters. The berms were nominally 1m high with a width of 5 m on one side and 8 m on the other side. The trial embankment comprised three 20 m sections with the end sections installed with wick drains (Section A, 1 m spacing, and Section C, 2 m spacing) and the middle section on undisturbed virgin ground used as a control section (Section B).

The pore pressure response shown in Fig. 5 is indicative of ongoing yielding.

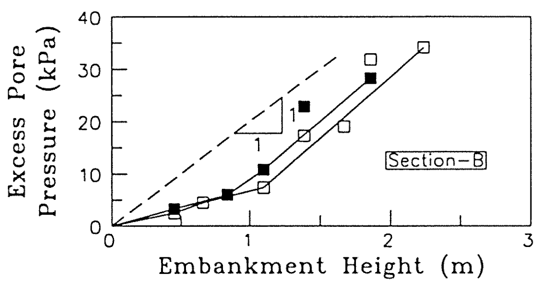

Figure 5. Relation between pore pressure and vertical total stress (Case B)

Figure 6 shows the lateral/vertical displacement ratios which are much lower than unity and thus is a poor indicator of ongoing yielding of the soft clay.

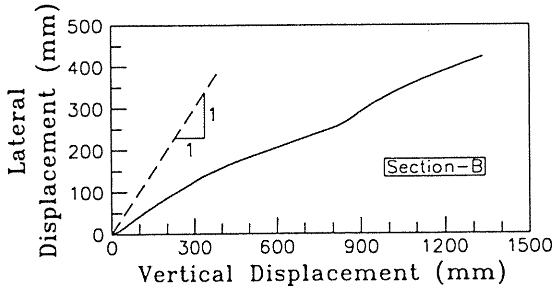

Figure 6. Variation in lateral displacement with settlement (Case B)

Figure 7 shows the ongoing settlements.

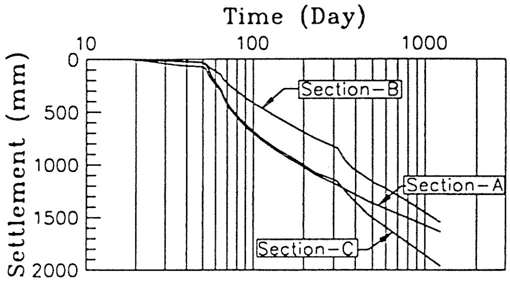

Figure 7. Time Vs Settlement Curve (Case B)

It is clear that the use of wick drains has not accelerated settlements to any great extent. Current settlements are in excess of 1500 mm for all 3 sections. The 2 m spaced wick drain section has settled the most. Assuming a drainage thickness of 5 m for the control section (B), the drainage times for Section A, in the idealised case should have been at least 25 times faster (assuming $C_v = C_h$). The ongoing settlements would suggest that the close spacing advantage of wick drains has probably been almost wiped out by installation disturbance of the wicks in these sensitive deposits.

6. CASE STUDY C: TRIAL EMBANKMENT AT COOMBABAH CREEK, GOLD COAST HIGHWAY

This section of the highway traverses a swamp with up to 13 m of soft clay, Fig. 8. The lack of a weathered crust is noted. Again, high LI values are indicated. The sensitivity of undrained strength based on the field shear vane is between 5 and 13 with an average of 6. The laboratory measured compressibilities, $C_c/(1 + e_o)$ ranged from 0.17 to 0.49.

The trial embankment consists of 3 sections. Two 12 m long sections adjacent to each other carry stone columns (1m ϕ and up to 16 m in length) at 3 m spacing (Section C) and at 2 m spacing (Section A). The lack of a weathered crust is expected to offer less passive resistance against the lateral buldging of the stone columns thus compromising their load carrying capacity. Adjacent to Section A is a 28 m long section on undisturbed ground (Section B). The height of the trial embankment was 2 m with a top width of 12 m on 1V:2H batters. The stone columns were installed with a jetting process; that is, using vibroflotation.

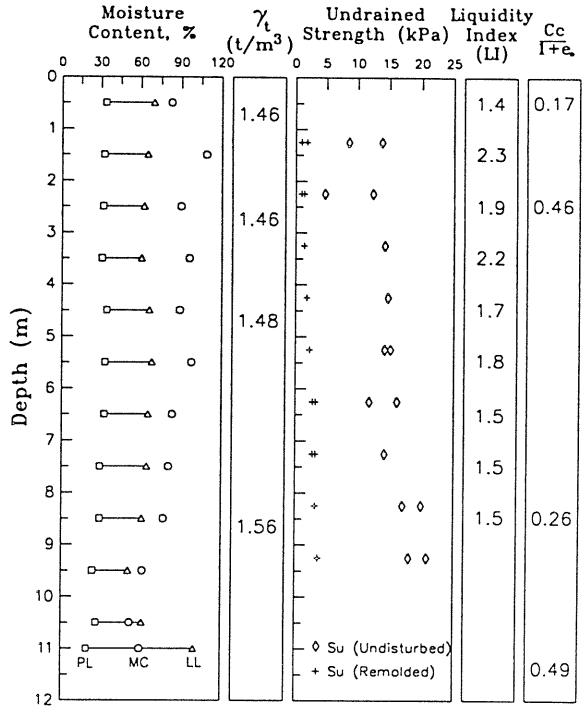

Figure 8. Geotechnical properties (Case C)

Figures 9 and 10 show the pore pressure and displacement data. Again, the excess pore pressures indicate yielding of the soft clay and even exhibit strain softening (ie, $B = \frac{\Delta u}{\Delta \sigma} > 1$).

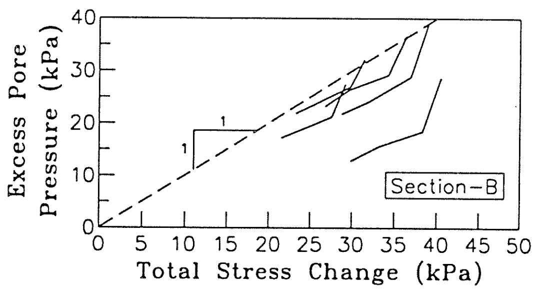

Figure 9. Relation between pore pressure and vertical total stress (Case C)

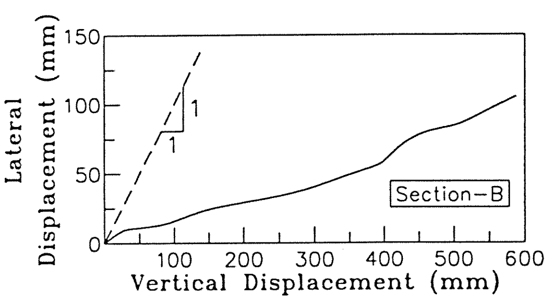

Figure 10. Variation in lateral displacement with settlement (Case C)

However, the lateral/vertical displacement ratio is not indicative of undrained behaviour. Figure 11 shows the ongoing settlements. The use of stone columns at this site does not indicate real gains either in terms of significantly reduced settlements or consolidation times. Further, the 3 m and 2 m spaced stone column performances are comparable. It is postulated that such stone column performances are due to disturbance caused to sensitive soft clays during installation. Settlement predictions have been carried out by Lerch (1996).

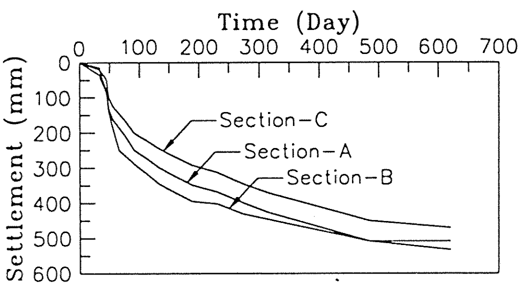

Figure 11. Time Vs Settlement Curve (Case C)

7. DISCUSSION & CONCLUSIONS

In principle, vertical displacement, lateral displacement and excess pore pressure parameters either individually or jointly could be considered as reliable indicators of onset of yielding and impending failure. However, the experiences reported in the literature are varied in that no one parameter has consistently been found to be always reliable (Crawford et al (1995), Ladd (1969)).

Based on the three trial embankments discussed in the paper, the following conclusions with respect to issues pertaining to control of stability during construction and effectiveness of ground improvement schemes can be made.

- The eastern coast belt of Queensland has extensive deposits of soft sensitive clays (LI = 1.5–2.5) of high plasticity.
- Embankments on soft sensitive clays discussed in this paper indicate that for construction control of stability, the lateral movements would not be a good indicator. This stems from the brittleness of sensitive soft clays, Ladd (1991).
- Pore pressure responses appear to be more indicative of the onset of yielding of the soft clays and can be considered a better candidate for control of stability.
- In these sensitive soft clays (LI = 1.5-2.5), the use of wick drains/stone columns has not proven to be effective and the use of such schemes in similar geotechnical conditions should deserve careful consideration.

Due to space limitations, other important issues such as in-situ property characterisation and review of design methods for wick drains/stone columns in the light of the trial embankments' findings have not been discussed and would be reported elsewhere.

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