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EMBANKMENTS CONSTRUCTED OVER SOFT CLAYS IN DARWIN

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ABSTRACT: Aspects of constructing an embankment on soft ground over the Darwin coastal fringe are discussed. Available compressibility data for soft clays from the Darwin area are compiled and correlations for compression indices are developed. Settlement data for an embankment constructed adjacent to Sadgroves Creek, Darwin Harbour is presented. Comparisons are presented between measured and predicted settlements.

1.0 INTRODUCTION

Extensive areas around the Darwin coastal fringe comprise soft riverine clay deposits. The clays are present in the intertidal zone beneath substantial mangrove colonies, and also as part of the sea floor substrate in Darwin harbour. Given the large tidal variation and the gentle sloping topography of the tidal zone, the soft clay environment is a significant one for coastal development and hinterland construction for Darwin.

The performance of embankments constructed over soft clays has been the subject of much research effort and practical experience for geotechnologists. For example, the trial embankment constructed at the Muar River, Malaysia as described by Poulos (1991) generated considerable interest. Predictions of stability and post-construction settlements by several parties were tendered with varying success. The outcome of that particular study must reinforce the notion that we are still some way off from methods that reliably predict the performance of embankments over soft clays.

An embankment has recently been constructed over a soft clay deposit adjacent to Sadgroves Creek, a tributary to Darwin harbour. The embankment forms a bund wall, and represents the first phase of a staged construction programme for a housing estate and marina complex. The wall will form the seaward barrier to tides during the construction phase, thereby creating a dry working environment for other elements of the project. The wall will eventually form part of the outer extent of the estate, with bulk fill placed behind the wall to create an elevated landfill for domestic land use.

The settlement behaviour of the bund wall was predicted as part of the initial design. Following construction, the actual settlement performance of the bund wall has been monitored. The settlement data have been made available to the author, and are presented in this paper. The objectives of this paper are as follows:

Objectives

1. Describe the geotechnical issues arising for urban development over Darwin intertidal clay deposits,

2. Present a summary of a body of geotechnical data compiled for soft clays in Darwin,

3. Present settlement data for an embankment constructed on soft clay in Darwin, and

4. Assess and compare the settlement of the embankment to the predicted performance based on the available database and experience gained from other soft clay sites in Darwin.

2.0 REGIONAL GEOLOGY AND GEOTECHNICAL ISSUES

2.1 Geomorphology of the Coastal Fringe

The Darwin coastal fringe refers to those areas within Darwin Harbour and the oceanic front extending to Lee Point in the east and Charles Point in the west. Figure 1 illustrates the extent of this coastal fringe. The region can be further divided into an oceanic zone and a riverine e, with the bulk of the soft clay sites occurring he riverine zone of Darwin Harbour. Darwin rbour has been formed by post-glacial flooding a dissected plateau, leading to an accumulation sediments over terrestrial lowlands. The liments have formed broad gently inclined, ck beds of sands and clays, with clayey position more common in the higher mangrove lonised areas. Michie (1987) describes the dimentation of Darwin harbour, and describes e origin of the sediments as terrestrial, and that some locations in the harbour, deposition is ll taking place on the tidal flats. Michie further rmises that the morphology around the harbour emonstrates consistency in origin.

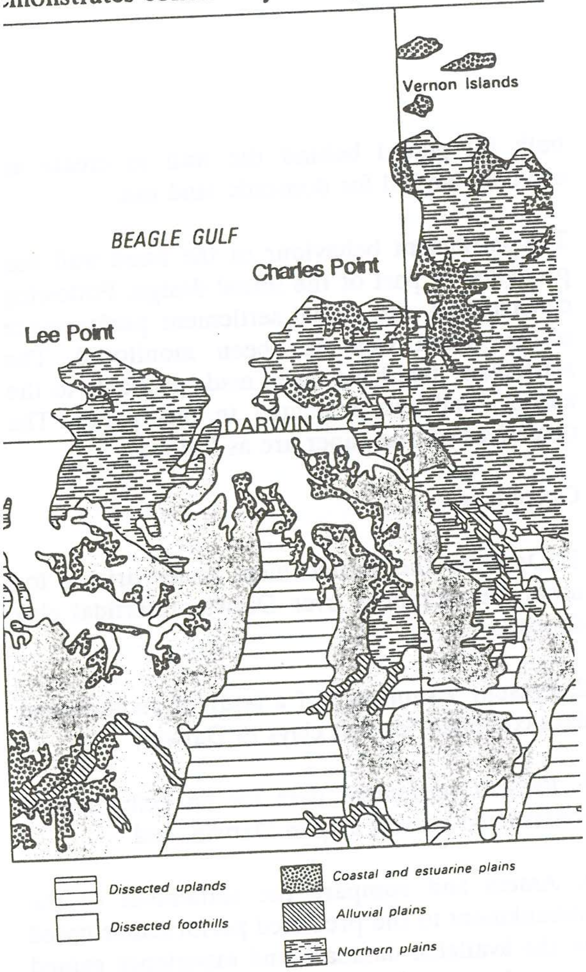

FIGURE 1 REGIONAL GEOLOGY

2.2 Geotechnical Issues

Constructing an embankment over soft clays on the Darwin coastal fringe presents a number of important issues to the geotechnical engineer. Fell et al (1987) describe the geotechnical performance problems typically encountered for embankments constructed on soft clay, including: short term stability of the fill, and magnitude and time of settlement. The key issues for embankments in Darwin include these, and to address them functionally and appropriately, the following factors and features of the Darwin soft clay environment should be addressed:

- undrained shear strengths typically in the range of 5 to 20kPa.
- clays are sensitive to extra sensitive, with remoulded strengths recorded as low as 1kPa.
- creep settlements are very probably large (however, quantification of this is as yet only limited).
- likelihood of large tidal movements, impacting on the phreatic surface in the embankment fill.
- the presence of a surficial clayey layer heavily matted with root vegetation, extending often to 1m deep.
- material underlying the soft clay sediments is often a clayey gravelly sand, which may have long term effective parameters not substantially greater than those of a consolidated clay bed.
- the thickness of some clay deposits may be less than 2m, and so consideration of alternate and more cost effective construction methods may be an issue.
- disturbance of 'undisturbed samples' due to travelling, as local laboratories are not well set up to perform comprehensive testing if that is required.
- wet season and dry season logistics of placing and compacting fill.

Ladd (1991) describes 'soft ground construction' as imposed loading sufficiently large to stress a cohesive foundation well beyond the preconsolidation pressure and into the normally consolidated range. However, this definition may not apply to many of the cases in the Darwin area, as embankment heights are not sufficiently large to push the effective stress well into the normally consolidated range. Yet these embankments have been constructed very much 'on soft ground'. Swamp dozers are the only form of plant able to work directly on the ground surface.

Duncan (1993) provides a description of the shortcomings in settlement predictions for sites underlain by soft compressible clays. Duncan identifies the four major problem areas as: 1) Difficulties in evaluating preconsolidation pressures, 2) Difficulties in selecting values of Cv for consolidation rate analyses, 3) Difficulties in assessing drainage path lengths due to interbedded sand lenses, 4) Shortcomings in conventional consolidation theory. Each of these issues discussed by Duncan are applicable considerations for the soft clays in Darwin, and this paper provides some preliminary discussion on these matters.

3.0 LOCAL EXPERIENCE WITH EMBANKMENTS

A number of embankments have been constructed over soft clay deposits in the Darwin coastal fringe after Cyclone Tracy. Many of these projects have opened up larger areas by creating a barrier to the tides and thereby allowing for reclamation of the wide intertidal flats that characterise many areas on the coastal fringe. As Darwin seeks to expand and develop in the coming years, the utilisation of these large and previously unused intertidal flats will become increasingly important (Ford, 1987).

Waterton & Ford (1984) describe the instrumentation of two embankments constructed over soft clays in the eastern part of Darwin Harbour. The two embankments described by these authors are Frances Bay Road and the Channel Island bridge approaches. Both of these projects were carried out by the Department of Transport & Works, NT. A brief description of each is presented.

Frances Bay Road

A 450m section of road embankment overlies soft clays, thicknesses of which extend up to 3.2m. The embankment was constructed in two stages, as instability was predicted if a full height of 4m was achieved in one phase. Consequently, the embankment was built to a height of 3m, and allowed to consolidate for a period of 2 years before the final 1m of fill was emplaced.

Channel Island Bridge Approaches

An access road to Darwin's power station crosses 2.3km of mangrove muds to reach Channel Island. The soft clays average at 4m, but extend up to 7m in thickness. Where the clays are thicker than 2m, the embankment has been constructed on stone columns.

Other major projects around Darwin where embankments have been constructed over soft clays include:

Cullen Bay Marina - as part of a housing estate and locked marina development, Darwin.
Dick Ward Drive - a road embankment constructed over soft mangrove muds, Darwin.
Bellamac Bundwall - a bundwall to reclaim tidal areas for landfill construction, Palmerston.

4.0 ASSESSMENT OF AVAILABLE DATA

A body of laboratory test data has become available from site investigation work undertaken for a number of projects where soft clays have required specific attention. Waterton (1993) has provided a summary of part of this data to the author. In addition to the Waterton data, the author has undertaken further assessment of settlement related parameters from laboratory test results. Strength parameters have not formed part of this assessment.

The projects from which laboratory test data is available include : Frances Bay Road, Channel Island bridge approaches, Darwin Waters Study, Darwin South Study. All laboratory test data relates to riverine clays of the Darwin coastal fringe. Table 1 provides a summary of the settlement related parts of the data set. All compression indices have been determined from oedometer testing. The Schmertmann (1955) correction to account for sample disturbance has not been applied.

Because of the expense of performing consolidation testing in Darwin, it is sometimes desirable to estimate the settlement behaviour from compression indices predicted from other classification properties. Compression indices have traditionally been predicted by using moisture content (w_n), void ratio (e), and liquid limit (LL). Azzouz et al (1976) summarise a number of empirical equations developed for clayey soils, as presented by Holtz and Kovacs (1981). An assessment of the data in Table 1 provides for two such empirical equations to be developed for the clays of the Darwin coastal fringe.

Compression Index versus Moisture Content

A reasonable correlation between these two parameters has been found. Figure 2 presents the plot of the available data, from which a linear regression has been performed (regression coefficient of 0.83). Equation (1) is presented based on this assessment.

$$Cc = 0.19 + 0.0065w_n\ (\%) \qquad \text{- Equation (1)}$$

This correlation appears to make sense, in that if a soil has a relatively higher moisture content then one would expect the soil to be more compressible necessitating a correspondingly

TABLE 1 AVALIABLE LABORATORY DATA

PROPERTIES		Darwin South	Frances Bay Road	Channel Island	Darwin Waters
LL	(%)	60-103	31 - 115	40 - 76	80 - 125
PI	(%)	38-77	13-88	21-51	54 - 100
Wn	(%)	71-102	52-98	44-194	77 - 95
Fines	(%)	91-98	NA	NA	92-96
OCR		1.0	3.4-4.6	1.0-12.2	1.2 - 1.7
Mv	(20-40kPa)	1.8e-3 to 6.9e-3	4.6e-4 to 2.2e-3	1.1e-3 to 5.5e-3	7.5e-4 to 3.3e-3
(mm2/kN)	(40-80kPa)	2.2e-3 to 4.1e-3	9.0e-4 to 2.4e-3	6.5e-4 to 2.4e-3	1.3 e-3 to 2.9e-3
Cv	(20-40kPa)	0.75 - 3.1	0.282	0.697	0.25 - 6.44
(m2/yr)	(40-80kPa)	0.52 - 0.89	0.245	0.76	0.22 - 0.55
Cc		0.66 - 0.80	0.54 - 0.75	0.11 - 1.44	0.63 - 1.03
Cr		0.088 - 0.137	NA	0.01 - 0.14	0.05 - 0.14

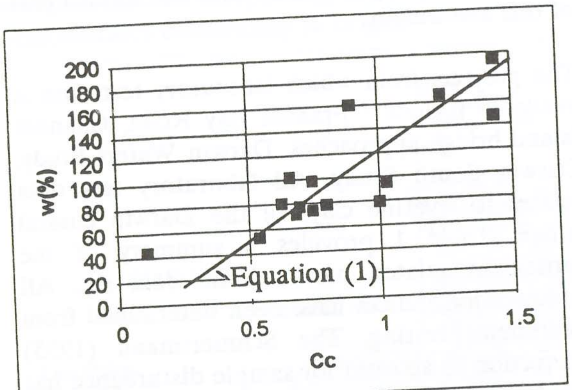

FIGURE 2 COMPRESSION INDEX VERSUS MOISTURE CONTENT

higher Cc. Ladd et al (1977) point out that whilst the relationship between moisture content, strength and deformation parameters has historically been linked, it is a major empirical simplification. However, in the absence of more detailed data, methods based on moisture content relationships are considered justified. Pandian et al (1991) for example, have investigated the effects of drying on the shear strength of soft marine clays, and correlate the results with moisture content and index properties of the soil.

Compression Index versus Recompression Index

A reasonable correlation between these two parameters has been found. Figure 3 presents the plot of available data, from which a linear regression has been performed (regression coefficient of 0.86). Equation (2) is presented based on this assessment.

$$Cr = 0.025 + 0.087Cc \quad \text{- Equation (2)}$$

Again, this correlation appears to make intuitive sense. The relationship suggests that if a soil exhibits a greater compressibility in the NC range then the soil will also exhibit greater compressibility in the OC range. Duncan (1993) indicates that the compressibility of a clay is about ten times as great at pressures above the preconsolidation pressure as it is at pressures below the preconsolidation pressure. Equation (2) supports this suggestion, as a Cc of unity predicts a Cr equal to 0.11Cc.

Co-Efficient of Volume Change (m_v)

The available data demonstrates reasonable consistency, with results generally within an order of magnitude for a particular stress range. Often however, lab data for the co-efficient of volume change is extremely variable, and its use should be exercised with caution. The mean value for two stress ranges has been determined and is presented as follows:

20-40kPa : m_v = 2.0e-3 mm²/kN

40-80kPa : m_v = 1.8e-3mm²/kN

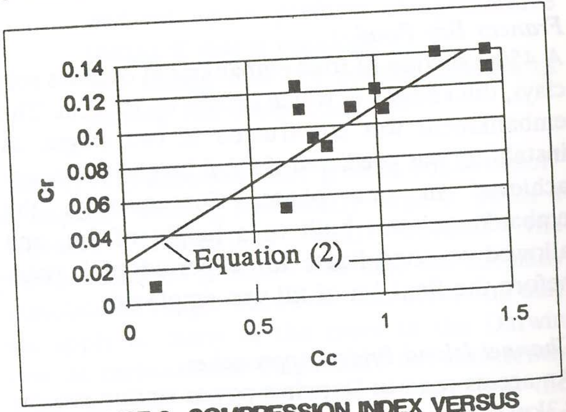

FIGURE 3 COMPRESSION INDEX VERSUS RECOMPRESSION INDEX

Preconsolidation Pressure

Settlement predictions rely on a sound understanding of the preconsolidation stress profile, as discussed by Duncan (1993). Laboratory testing affords the best method to do this, however, in the absence of laboratory data, estimates must be made. The preconsolidation pressure is of significant importance in the surficial overconsolidated crust if this forms a substantial portion of the soft clay profile as is the case for Darwin soft clays. Compressibility of a highly OC crust is usually slight, as most of the settlement will occur in the underlying softer materials.

Figure 4 has been prepared from the available data, and shows Liquidity Index (LI) against preconsolidation pressure (p'_c). In the overconsolidated crust the LI is expected to be less than unity, due to moisture contents lower than the LL. Similarly, LI is expected to be greater or close to unity at depth, where moisture contents are commonly close to the LL or higher. Figure 5 shows how a theoretical relationship between these two parameters is likely to be. Use of such a plot would enable a reasonable estimate of the preconsolidation pressure in the overconsolidated crust. However, the available data does not provide convincing support to this postulation. A slight trend is hinted by the data for the OC arm of the plot, however the trend is considered far from a useable correlation for the soils tested.

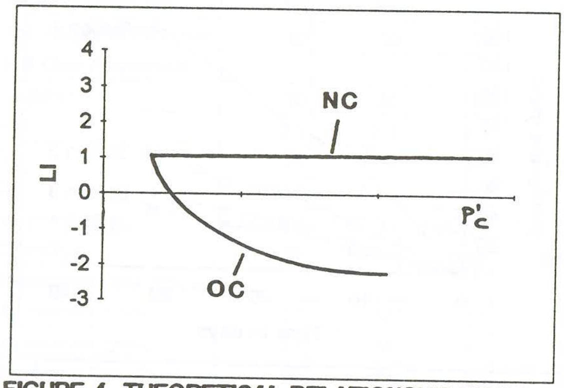

FIGURE 4 THEORETICAL RELATIONSHIP BETWEEN LIQUIDITY INDEX AND PRECONSOLIDATION PRESSURE

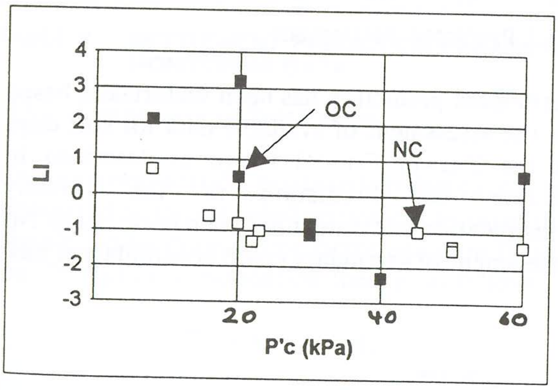

FIGURE 5 DATA FOR LIQUIDITY INDEX VERSUS PRECONSOLIDATION PRESSURE

Higher strengths associated with the weathered crust have been recognised (Fell et al, 1987; Lefebvre et al, 1987; Burn et al, 1988) as a distinguishing feature of their presence, and so their limit can be reasonably well determined based on the vane shear profile.

Co-Efficient of Consolidation (Cv)
The available laboratory test data demonstrates a high degree of variability for the two stress ranges considered. All data relates to oedometer test results, with interpretations based on the Casagrande t_{50} method. As the data set for the 20 to 40kPa stress range contains values which are likely to strongly affect an arithmetic mean (the distribution of values likely represents a skewed normal, perhaps a log-normal), the median values have been determined and are as follows:

20-40kPa :	0.25 - 6.44 m^2/yr
	Median = 0.69 m^2/yr
40-80kPa :	0.22 - 0.89 m^2/yr
	Median = 0.53 m^2/yr

The data for the lower stress range demonstrates typical variability associated with the Cv parameter. Duncan (1993) indicates the value of Cv for a given clay is about an order magnitude larger at pressures below the preconsolidation pressure as opposed to pressures above the preconsolidation pressure. The data for Darwin soft clays complies with this general trend although it may not be as pronounced as Duncan suggests; the variability in results for the lower stress range requires a more rigorous assessment to further investigate this relationship.

The drainage path length for a soft clay deposit is a critical parameter when assessing time rates for consolidation. Experience has shown for clays of the Darwin coastal fringe (Carr, 1993), that settlement rates generally correlate to a drainage path length of approximately H/4 (where H is the thickness of the soft clay bed) when clay thicknesses are in the order of 2 to 4 m. This relationship appears to breakdown for thicker and deeper beds of soft clay, suggesting that drainage path lengths are more a function of the geomorphology of the deposits than the geometry. These drainage paths reflect the interlayering of shelly gritty sands that have been observed in soft clay profiles. These layers are noted by Michie (1987).

5.0 CASE STUDY - PREDICTION VERSUS PERFORMANCE

5.1 General

The bundwall recently constructed adjacent to Sadgroves Creek has provided an opportunity to juxtapose settlement prediction alongside recorded settlements. As no laboratory consolidation testing was undertaken for clays underlying the bundwall, the project lends itself to the prediction of settlement based on precedent experience and related laboratory data. The data presented and described in Section 4.0 of this paper can be used for this purpose.

The soils beneath the bundwall posses high moisture contents. Ten samples were tested, the average calculated as $w_n=139\%$, with a range of 115% to 159%. The high moisture contents can be partly attributed to the high organic content of the soil, as organic matter can tend to hold free moisture in its structure. These high moisture contents typically associated with organic soils may therefore not represent the actual interparticle moisture content of the soil matrix. Like calcareous sands that posses a characteristic intraparticle moisture content, these organic soils might posses a fourth phase with its own moisture content relationships, which in turn may affect the engineering behaviour. Further consideration is required to understand this more fully.

5.2 Stability of the Bundwall

Stability considerations of the bund wall are not presented in detail in this paper. A cross-section of the bund wall is shown in Figure 6, illustrating the use of berms to stabilise against short term slope failure through the soft clays. As no instability of the bundwall has been reported at the time of writing (a period of two months after construction), it appears that the embankment is past the critical time when excess pore pressures are at their greatest.

5.3 Settlement Behaviour of the Bundwall

5.3.1 Monitoring Data

Four locations (Stations 1, 2, 3 and 4) along the 250m bundwall have been designated as the settlement control points with small survey monuments constructed at each station. The stations have been installed along the centreline of the bundwall, and all measurements relate to vertical settlement.

For two of the Stations (1 and 2), monitoring began approximately 14 days after the wall was completed. Therefore, the embankment had been undergoing consolidation for 14 days under full load prior to any settlement record. Initial elastic displacements would also have occurred in this time. Similarly, at Stations 3 and 4, the embankment had been consolidating for approximately 7 days under full load prior to monitoring.

Figure 7 presents the time-settlement data for each of the stations, presented also in Table 2. The horizontal time axes represents the relative time from the start of monitoring, the vertical axes representing the corresponding relative settlement.

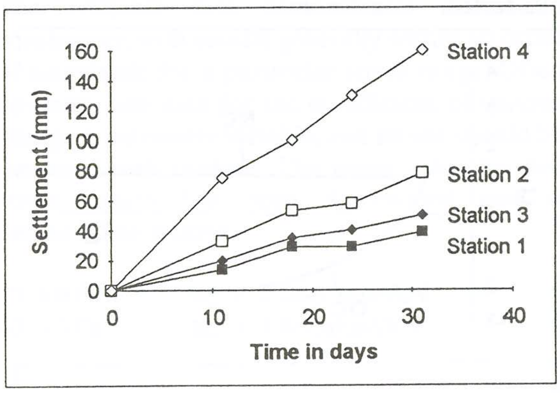

FIGURE 7 TIME–SETTLEMENT DATA

5.3.2 Predicted Settlement

Settlement prediction has been undertaken based on the assessment of available data for soft clays of the Darwin Coastal fringe as described in Section 4.0. Prediction of the primary consolidation settlement has been performed. No assessment of secondary creep consolidation has

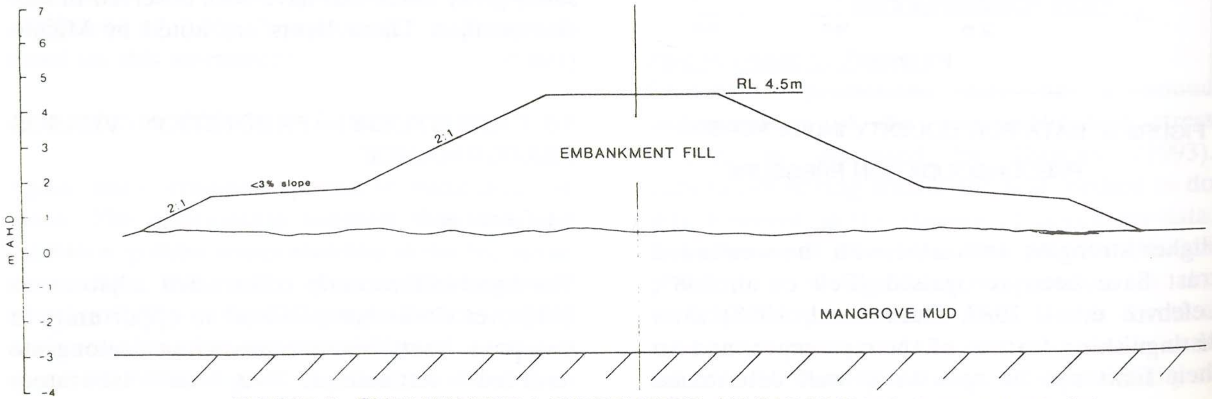

FIGURE 6 EMBANKMENT CONSTRUCTED AT SADGROVES CREEK, DARWIN

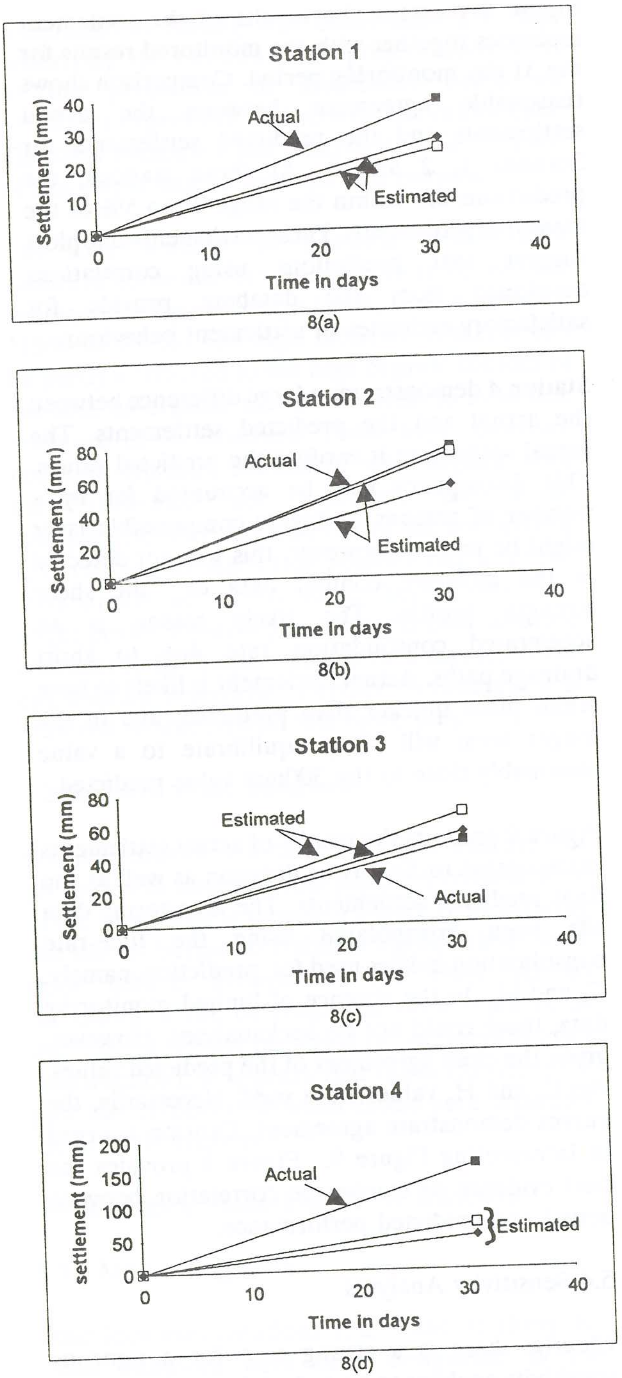

FIGURE 8 COMPARISON OF ACTUAL AND ESTIMATED SETTLEMENTS, 31DAYS

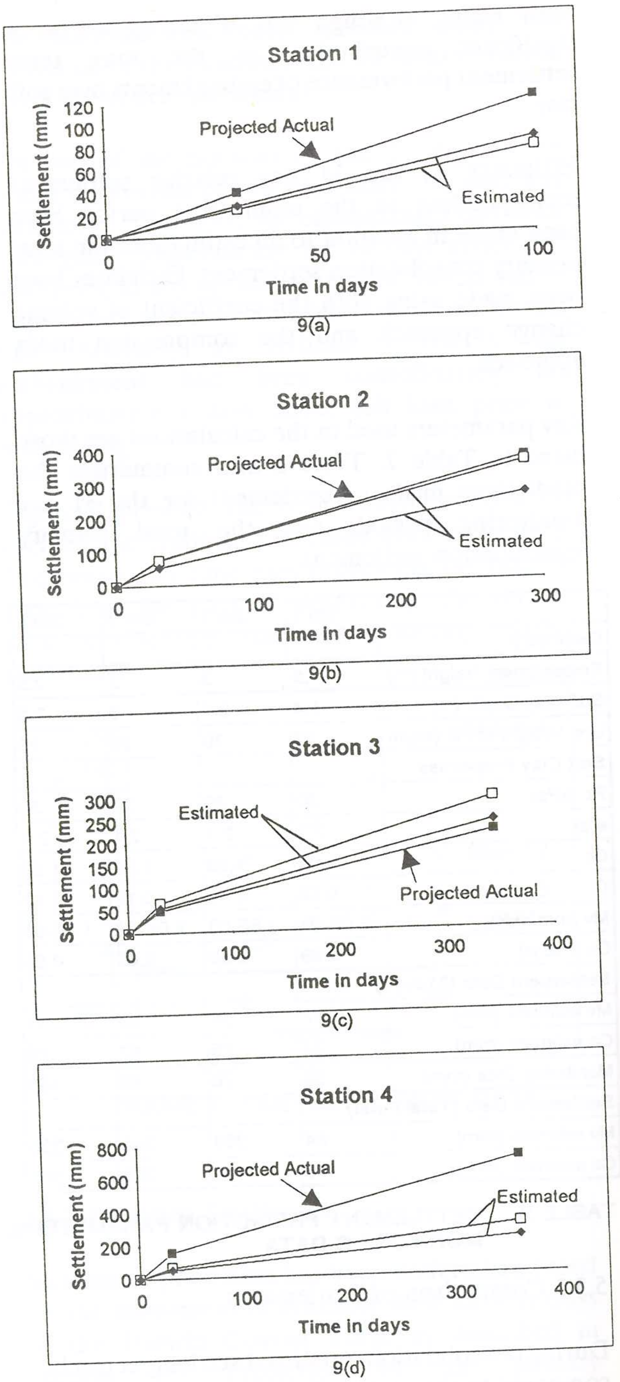

FIGURE 9 COMPARISON OF PROJECTED ACTUAL AND ESTIMATED TOTAL CONSOLIDATION SETTLEMENTS

6.0 CONCLUSIONS AND LIMITATIONS

1. Soft clay deposits are present in the Darwin vicinity exhibiting consistent geomorphology. The distribution of the deposits around the coastal fringe create the need for adequate engineering when development is initiated on these sites.

2. A body of geotechnical data for soft clays of the Darwin coastal fringe has been compiled and assessed for consolidation indices. Correlations for moisture content (w_n%) versus compression index (Cc), and a correlation of compression index versus recompression index (Cr) has been presented.

3. Settlement data available for an embankment constructed on soft clay has been presented. These settlements have been compared to predictions of settlement based on the assessment of available data from other sites. Comparison has shown generally close agreement of actual and predicted settlements.

4. There remains wide scope for further

assessment of the available data base, both in terms of the laboratory test data and the body of settlement monitoring data. With a larger database, analyses will become further refined. However, these type of indirect analyses should never replace detailed laboratory work with commensurate analysis of performance. In the absence of a strong laboratory testing programme, the methods described in this paper are recommended as a first stage estimate.

Acknowledgments

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