The paper was published in the proceedings of the 9th Australia New Zealand Conference on Geomechanics and was edited by Geoffrey Farquhar, Philip Kelsey, John Marsh and Debbie Fellows. The conference was held in Auckland, New Zealand, 8 – 11 February 2004.

A proposed geological model and geotechnical properties of a NSW estuarine valley: A case study

D T Bishop
BSc (Hons), UWA
PhD Researcher University of Newcastle

Summary: The estuarine valleys of the east coast of Australia contain extensive soft clay deposits. The complex spatial distribution of these deposits and the variability of their geotechnical properties pose major problems for the development of the Pacific Highway upgrade between Sydney and Brisbane. Sections of the new road will cross extensive deposits of estuarine clay with thicknesses ranging from 8 to 30m. The case study presented is of the proposed Ballina Town bypass in the Richmond River Valley in Northern New South Wales. This paper presents a geological model developed from extensive site investigations, and its use to predict the distribution of geotechnical problem areas. Two major paleo-weathering horizons are identified in the valley, forming significant structural boundaries. These horizons resulted from low-stand sea levels during the Early and Late Pleistocene. The lower horizon separates two stages of deposition within the Pleistocene deposits, while the upper horizon separates the Pleistocene and Holocene sediments. The thick Holocene clays have resulted from rapid sea level rise during the early part of the Holocene.

INTRODUCTION

Expanding populations in the coastal regions of Eastern Australia are gradually outgrowing the existing transport infrastructure. Of major concern is the main North-South link road connecting Sydney and Brisbane. A large proportion of this coastal highway is currently being upgraded, with much of the new construction confined to marginal land corridors that have previously been avoided. The eastern seaboard of Australia is dominated by a succession of easterly flowing rivers that drain the adjacent ranges into the Pacific Ocean. In the lower reaches of these river valleys are extensive estuarine deposits with a complex geologic structure. This paper focuses on the site of the Ballina Bypass (Figure 1) that is to be constructed over the floodplain and underlying estuarine deposits, near the mouth of the Richmond River in Northern NSW. Data have been obtained from initial route and first stage investigations.

One of the difficulties with the interpretation of geotechnical data is the interpolation and extrapolation of a finite and limited data set in order to predict and model the performance of large scale structures such as road embankments. Particularly in marginal marine environments, uniformly thick sequences of homogenous sediment are uncommon and the extrapolation of soil properties across large areas is enhanced by the use of a geological model. Utilizing the principles of sequence stratigraphy and a depositional model, it is possible to correlate packages of sediment and gain an important insight into the areal extent of layers. This is highly significant in the case of interbedded sand layers that may or may not act as drainage pathways during the consolidation of adjacent clay layers. One of the key features of Recent marginal-marine environments is the impact of eustatic fluctuations in sea levels on sediment distribution (Roy, Hudson et al. 1995). Rising sea levels result in the flooding of coastal valleys and the development of estuarine environments. Coastal sand barriers form adjacent to headlands and interbedded fluvial-estuarine-marine sediments are deposited behind them. Falling sea levels cause coastal rivers and streams to incise, the removal of large volumes of existing sediments and the development of extensive weathering surfaces (Kenney 1964). With exposure above the water table, sediments can become oxidised and indurated; certainly clays become stiff and fissured, sometimes to great depths. These processes are substantially controlled by the prevailing climatic conditions of the period.

GEOMORPHOLOGY

The lower Richmond River is characterised by a low, narrow floodplain formed by Holocene sediments (<1m AHD) behind a barrier dune complex (up to 20m high). Inland, the floodplain is bounded by gentle to steep slopes of Tertiary basalt (up to 50m above sea level) and minor outcrops of Triassic and lower Palaeozoic sediments (Pogson and Hitchins 1973). Two creeks, Emigrant and North Creek, feed the lower Richmond River channel. The head-waters of the creeks are located in the basalt hills to the NE. The last 20 km of the Richmond River's flow is constrained to occur parallel to a coastal sand barrier before exiting at Ballina. Much of the area has been cleared but remnant mangrove swamps and salt marsh are found along the lower reaches of the creeks and over a large area of the North Creek catchment. The floodplain extends to around 5km up the Macguires and Emigrant Creek valleys and nearly 15km upstream in North Creek. These features are shown in Figure 1.

The hydrology of the river system has been considerably altered since European settlement with major levee construction and drainage of the floodplains. Current marine sedimentation is limited to a tidal delta that is visible up to 4km inland from the river mouth. The deposits consist of 600 to 700m long, lobate-shaped, marine sand bodies. Upstream, sediment deposition is limited to floodplain deposits formed during major flooding events and temporary deposits within the main channels. Frequent and major flooding events recorded during European settlement are a result of a mean annual coastal rainfall of around 1700mm, of which approximately 60% falls during the five month period from December to April (Brierley, Brooks et al. 1995).

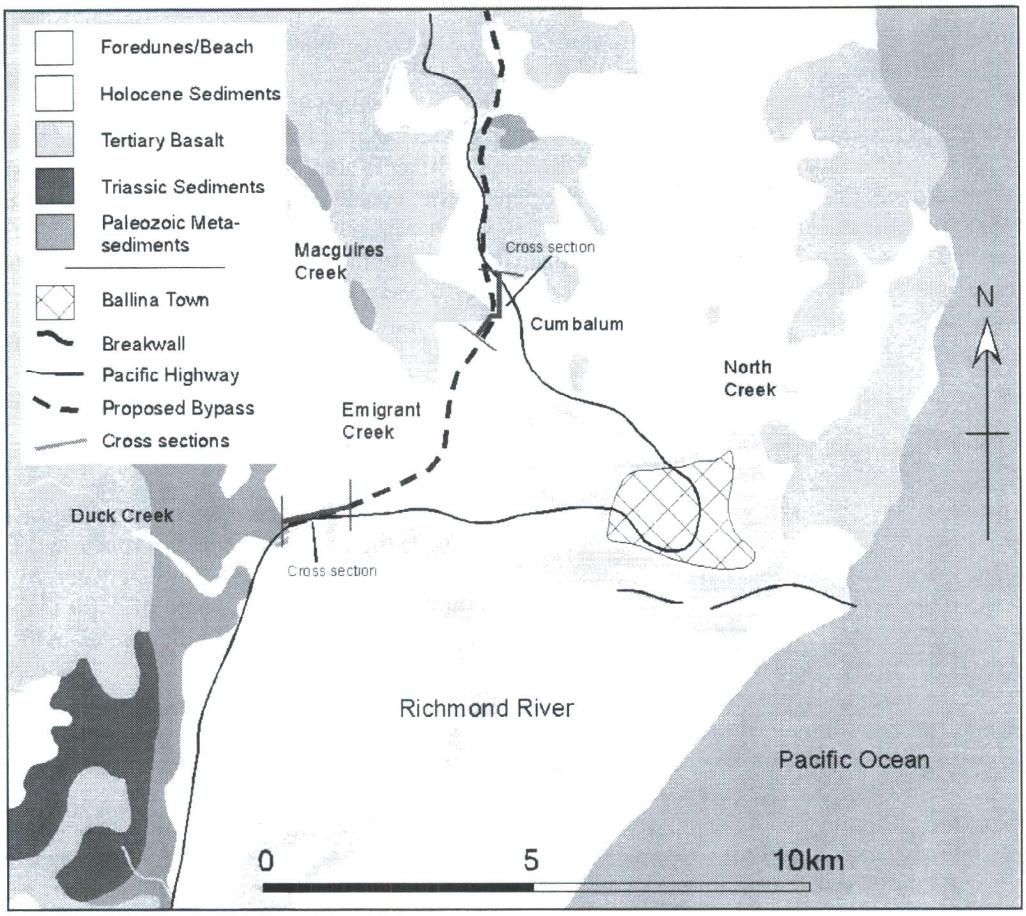


Figure 1. Surface geology and major features in the study area. Modified from Pogson and Hitchins (1973).

GEOLOGICAL MODEL

The Clarence-Morton (CM) Basin unconformably overlies a basement of extensively deformed and folded metasediments of Palaeozoic age. The CM Basin rocks are Mesozoic (Triassic-Jurassic) in age and consist of sandstones, siltstones and shales. These are, in turn, unconformably overlain by Tertiary volcanics consisting of basalt, tuff, obsidian and interbedded sediments (Pogson, Hitchins 1973, Drury 1982). In many cases, the basalt flows have filled topographic lows in the underlying Triassic-Jurassic and Palaeozoic sediments. It is within this geological and geomorphological framework that the Quaternary sediments have been deposited.

The structure of the paleo-topographic surface between the unconsolidated Quaternary sediments, and the underlying, older basement rocks has been determined by large-scale resistivity work and regional drilling (Drury 1982) and is further defined by drilling undertaken as part of the route investigation for the new Pacific Highway (Robert Carr & Associates 2001; Robert Carr & Associates 2003). It is generally believed that the Richmond River bedrock channel incised the basement rocks to a depth of at least -53m AHD while the sea level was at a low-stand, during a period of significant global glaciation. Available information suggests that the bedrock paleo-channel generally underlies the current main river channel. Away (to the north and east) from this channel, the bedrock forms an undulating platform (approx. 35m deep) that shallows rapidly approaching the floodplain margins. Deep bedrock channels, to -46m AHD, lie at the bottom of the adjoining valleys that contain Emigrant, Macguires and Duck Creek, and these extend to the main Richmond River Channel. The general topography of this erosion surface is gently undulating beneath the central floodplain area, becoming progressively steeper within the adjoining valleys and beneath the main channels. A shallow basalt platform appears to underlie the North Creek channel, possibly limiting the depth of the Quaternary sediments to around 17m AHD in that area.

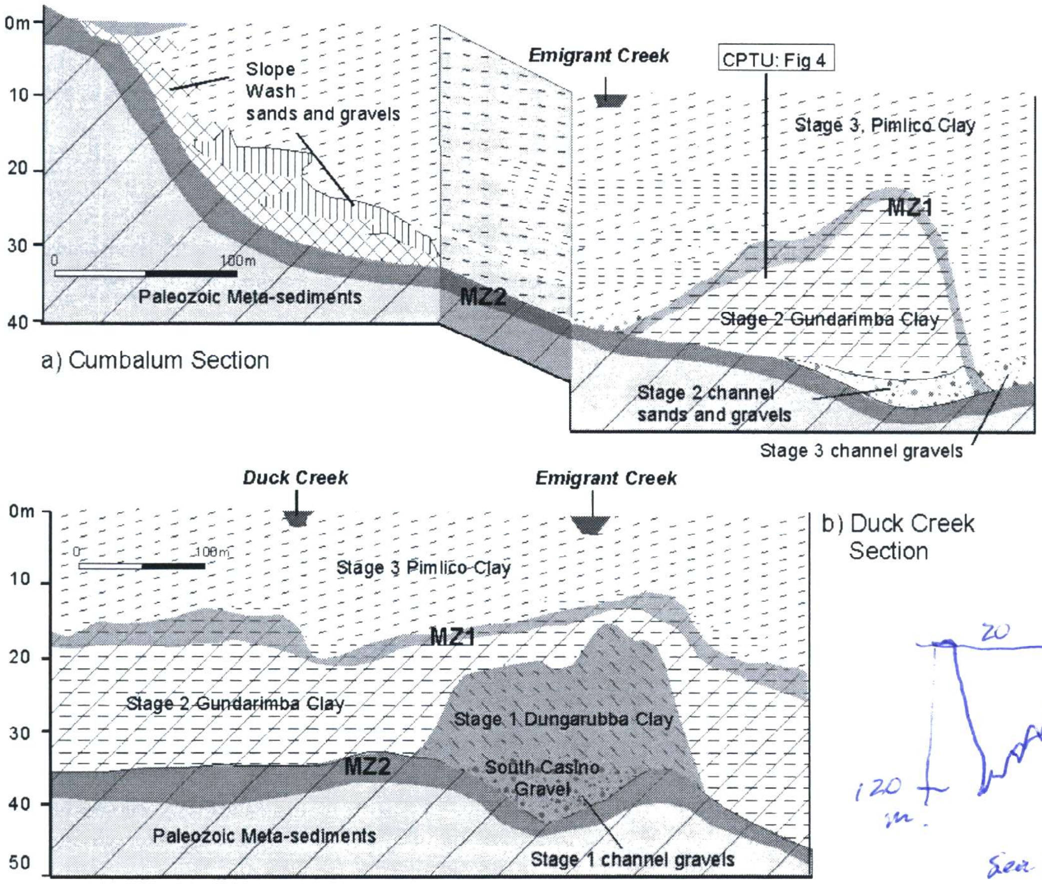
Three distinct stages of Quaternary deposition have been identified from drill core interpretation. These stages have been recognised from sediment facies changes and are separated by zones of oxidization and indurated clay. The stages of deposition, and the alteration zones that bound them, are illustrated in the cross sections shown in Figure 2 and located as shown in Figure 1. They are described as follows.

- Stage 1: Some deeper bedrock channels (40m) contain 1-2m thick, dense, heavily altered, fluvial sandy-gravels containing pebbles and/or cobbles of basalt and chert, with interstitial clayey-sand. There is evidence of a fining upwards sequence of very stiff clays that are heavily oxidized and that are now mostly eroded. Locally, these altered clays may overlie the earlier gravels, and they occur in isolated remnant mounds that extend up to -15 AHD (Figure 2b).

A highly oxidised and indurated alteration horizon termed MZ2 has been identified, affecting the surface of the basement rocks and the full thickness of the overlying Stage 1 channel gravels and clays (Figure 2b).

- Stages 2 and 3: The Stage 2 and 3 deposits are each characterised by generally fining up sequences, which grade from gravels and sandy-clays at lower levels, to dominantly dark grey shelly muds in their upper levels.

Both Stage 2 and 3 unconformably overlie the Stage 1 deposits, separated by the MZ2 horizon. Stage 3 unconformably overlies Stage 2 and is separated by a second oxidation horizon, termed MZ1. MZ1 is between 1-3 meters thick and affects the upper portion of the Stage 2 clays. In all boreholes, the clay fraction is dominant above -10m AHD, and unlike the zones below -10m AHD (Figure 2a) almost no sandy layers have been observed.



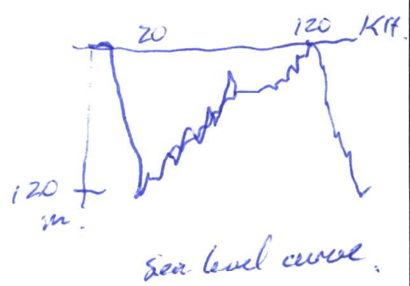


Figure 2. Interpreted sections (Figure1) derived from borehole logs and CPTU interpretation.

The elevated subsurface structures and deep channels identified in both the Stage 1 and 2 sequences (Figure 2a and b),are interpreted as the remnants of levee-bank structures and paleo-channels. Subsequent deposition events have infilled and covered these structures. In the vicinity of the junction of Duck and Emigrant Creeks, the Stage 2 and 3 clay units are also separated by a 2-5m thick, dark brown, medium-grained sandrock unit.

The units comprising the three deposition stages have been broadly correlated as follows to units defined by Drury (1982) in studies of sediment units further upstream in the Richmond valley:

- The Stage 1 lower gravel-cobble unit correlates to the South Casino Gravel
- The Stage 1 oxidized clay (affected by the MZ1 alteration event) is the Dungarubba clay.
- The Stage 2 clay, the lowermost of the two fining up units is the lower is the Gundarimba clay.
- The Stage 3 upper estuarine clay referred to as the Pimlico Clay (Figures 2a, b).

The sandrock unit, between Stages 2 and 3, with its distinctive brown organic colouration, is correlated to the Broadwater Sandrock.

In the study area, the Pimlico Clay (Stage 3) is found as a covering deposit in all sections west of Ballina and ranges from 10-40m in depth. The thick deposits of Pimlico Clay are localized within the incised paleo-channels, bounded below by MZ2. Upstream along Emigrant creek, the Pimlico Clay is the dominant unit (Figure 2a) while in the central flood plain area, the Pimlico Clay overlies nearly 20m of Gundarimba Clay (Figure 2b). Upstream of the study area, along the main Richmond River channel, the thickness of Pimlico Clay decreases rapidly and it becomes a minor unit occupying only the main paleo-channel (Drury 1982).

DEPOSITIONAL MODEL

The interpretation of the sedimentary sequence within the study area depends heavily on the interpretation of the origin of the alteration layers. The alteration horizons are considered to record weathering that occurred during periods of sea level fall (Kenney 1964), corresponding to periods of global glaciation. Another consequence of a sea level low stand is the exposure of former sediment deposits, making them prone to renewed erosion and channel incision. Although depositional environments can exhibit significant variation both spatially and temporally, major weathering and erosion events associated with sea level low stands tend to be ubiquitous and are particularly useful for identifying the demarcation between depositional events (sequence boundaries).

Uranium and radiocarbon dating indicates that the Stage 1 South Casio Gravel and Dungarubba Clay, and the Stage 2 Gundarimba Clay, are all of Pleistocene age, deposited prior to the sea level high-stand at 120,000 BP (Drury 1982; McMinn 1992). The existence of the MZ1 horizon, of indeterminate age, is consistent with the accepted interpretation of oscillating sea levels during the Pleistocene (Walker 1999). The erosion surface MZ2 resulted from the last major glaciation event (sea level low-stand) at around 17,000 BP. The paleo-levee-bank structures identified in the MZ2 horizon (Figure 2a) formed by the incision of coastal streams into the Pleistocene Gundarimba and Dungarubba units during the last sea level low-stand. Between 17,000 and 5,000 BP, sea levels rose rapidly, some 150m, and the deposition of the Pimlico Clay (Stage 3) appears to correspond to this (Holocene) period. Thin floodplain deposits (Recent) of <1m now cover the surface and correlate to flood events or small rises in sea level since that time (Kenney 1964; Roy 1984). Figure 3 shows the distribution of the Stage 3, Holocene, sediments across the study region.

The sandrock unit beneath the Pimlico Clay is interpreted as a marine sand unit, possibly deposited as an early tidal delta formed during a lower sea level still-stand. It is generally thought that the cementation and induration of this layer is the result of leaching and re-deposition of humic material from overlying or adjacent swampy areas (Packham 1969).

As sea levels stabilised in their current high-stand position, the landward migration of open marine conditions ceased. The occurrence of interbedded sands and estuarine muds below -10m AHD in the Stage 3 Pimlico Clay indicates higher energy, rapidly changing deposition conditions, which is a feature of wave dominant or open estuarine conditions (Roy, Hudson et al. 1995). Within the narrow river valleys (e.g. Emigrant Creek) small sand tidal deltas would have existed until the main coastal barrier formed. The generally rocky coastline of NSW provided headlands that became nodes for the stabilization of shoreface conditions. Barrier bars developed between the headlands, in response to the northward migration of marine sand, and estuarine conditions developed behind the barriers (Roy, Hudson et al. 1995). The absence of significant sand in the Pimlico Clay above -10m AHD is interpreted to correspond to the formation of the coastal barrier, which restricted marine sedimentation, and formed quiet estuary conditions. This theory is further supported by the presence of the bivalve, *Notospisula trigonells* throughout the upper portion of the deposit. This bivalve is found only in quiet estuarine environments, away from turbulent tidal channels and estuary mouths (Walker 1999). Within the estuary, fluvial-deltaic conditions prograded outwards, and as a result, estuarine mud and sands were intermingled with slopewash gravels and clays (Figure 2a). Over time, wide tidal flats shrank and water courses became confined to meandering systems, with swamp vegetation and mangroves stabilising the area. This is the system that would have been observed in the estuary prior to European settlement. At this point, further deposition is limited to thin fluvial over-bank deposits formed during major flooding events.

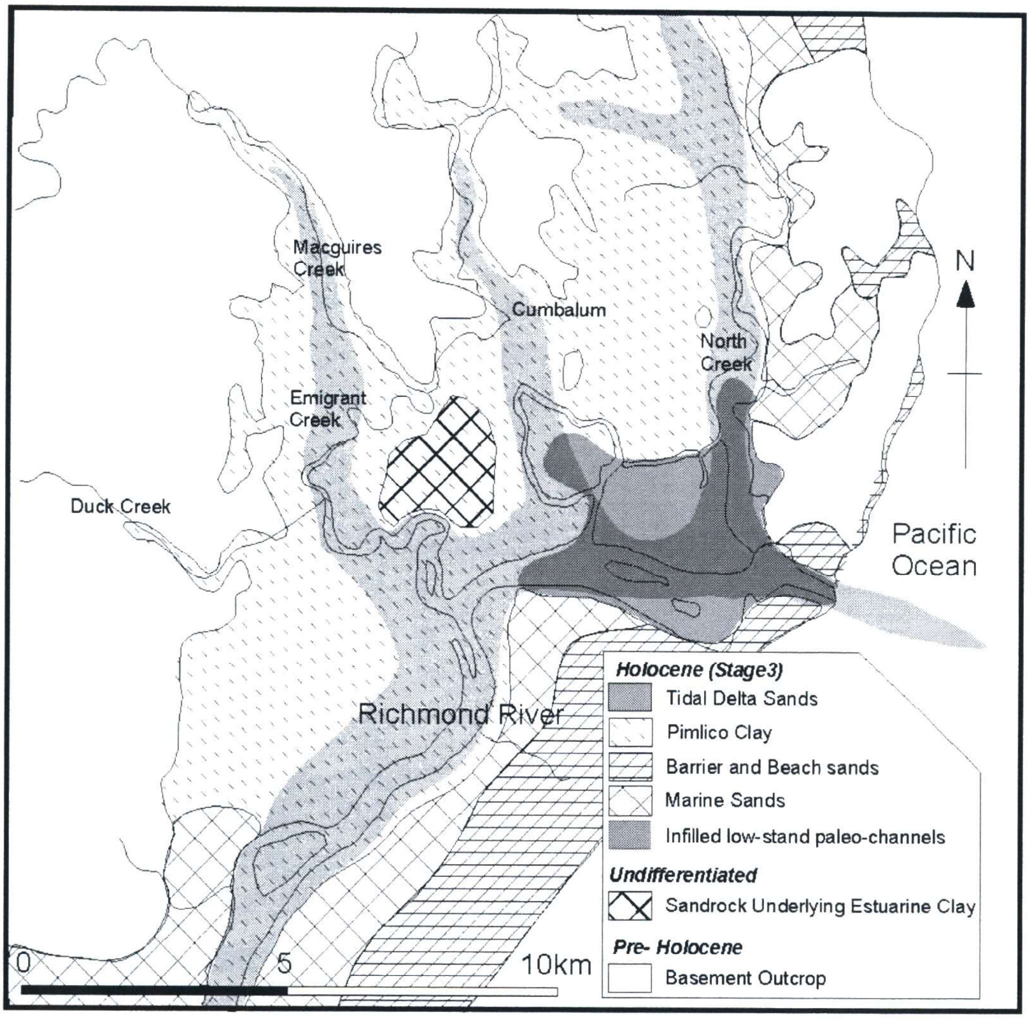


Figure 3. Distribution of Holocene sediments and buried, low stand paleo-channels

GEOTECHNICAL PROPERTIES

Figure 4 shows typical borehole and cone penetrometer data for the location indicated in Figure 2a. The depositional model developed in the preceding sections can be used to make a more informed interpretation of geotechnical information gathered from the site. A summary of the characteristic geotechnical properties available for each unit is presented below. Although these data are taken from a representative borehole and CPTU test at Cumbalum, these values have been correlated with more widespread data, and are considered representative of the identified units.

- Surface crust: This layer is generally found in those areas that have been cleared and drained. The main differences between this layer and the underlying Pimlico Clay are likely to result from alteration due to drying and wetting cycles and biogenic activity (Bjerrum 1967). The cone tip resistance (qt) values are around 700 kPa and Su_{vane} values are between 75-100kPa. Orange-brown mottling and fissuring is a common feature of this layer.
- Pimlico Clay: The clay has extremely high moisture content, up to around 130% at 5m depth. Undrained shear strength ranges from 16-33kPa while q_t is around 0.2-0.3 MPa.
- Woodburn sand (Broadwater sandrock): CPTU test were unable to penetrate this layer in many locations due to the induration, but pumping tests have shown that this unit has a low porosity (Drury 1982).
- Gundarimba Clay: The natural moisture content of the middle clay unit is considerably lower, around 60%, and the PL and LL are 30 to 100 % respectively. These are similar to the values in the surface crust. The q_t values rise sharply to around 1 MPa in the mottled zone but then fall off again with depth (Figure 4), consistent with the observation that the lower portion of this clay is unaffected by weathering. Su_{vane} data for the mottled zone is over 100 kPa but falls back to around 40-50kPa in the lower region.
- Dungarubba Clay: No moisture content data is available for this clay but borehole logs indicate that the clays are hard and moist, suggesting values much lower that the upper clays. The q_t values rise sharply to over 3 MPa, while the excess pore pressure drops to hydrostatic, probably as a result of open fissures observed in this zone.

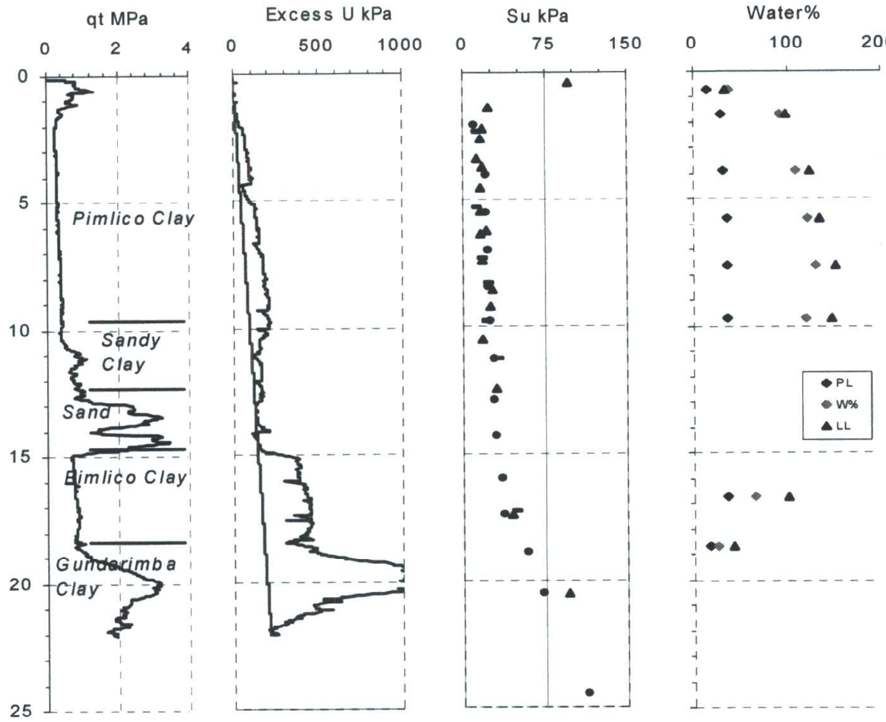


Figure 4. Characteristic properties of the Quaternary sediments. Data taken from a single Borehole and CPTU at Cumbalum. All properties plotted verses depth (m)

REGIONAL PREDICTION AND INTERPRETATION

Of primary concern for embankment construction in this area are the thick sequences of soft compressible clay, of which the Holocene Pimlico clay is of greatest concern. The geological model predicts that around 10m of this estuarine clay will underlie a large proportion of the lower reaches of the floodplain. The thicker sequences of this clay, >15m, are located only within relatively narrow zones defined by the paleo-channels (Figure 3), which were incised up to the last low-stand at 17,000BP. Within the narrow valleys (Figure 2a, 3) most of the Pleistocene deposits have been removed, as a result of concentrated erosion during low-stand. These valleys have subsequently been in-filled with thick deposits of highly compressible Pimlico Clay. Embankments constructed over the paleo-channels and in the valleys, where the Pimlico clay is thickest, are likely to undergo the greatest amount of settlement. The channels, however, are of limited width compared to the length of the bypass, and utilizing a targeted CPTU testing program guided by a model of the type developed here, it will be possible to identify these zones and limit construction over them.

The performance of any embankment is also likely to be affected by the orientation of the weathering surfaces present within the lower horizons (e.g. MZ1, MZ2). In both the Duck Creek and Cumbalum sections (Figure 2a, b), areas of the MZ2 horizon dip steeply, especially adjacent to the infilled channels. This means that the thicknesses of the overlying, sensitive Pimlico Clay varies considerably over a relatively short distance. In the case of embankments constructed non-symmetrically over these areas, there may be significant problems relating to differential settlement. As a consequence of the differential settlement the MZ2 horizon may also provide zones for the localisation of stress and possible premature failure.

Another significant factor in determining embankment performance is the identification of laterally extensive drainage layers for excess pore pressure dissipation. There are two such units in the study area. Although the Broadwater sand rock unit has low conductivity, uncemented, permeable sand is generally associated with the base and/or top of the unit. Due to this layer's lateral extent, it should provide two-way drainage during consolidation of the upper and lower clays in this area. The upper MZ2 zone, being the most recent, is predicted to be laterally extensive and although iron oxide precipitation and hard-pan development are likely to reduce permeability (Velde 1995) the presence of extensive sand-filled fissures should provide good drainage. In the absence of the sandrock unit, this desiccated layer should still provide improved drainage capabilities.

CONCLUSIONS AND RECOMMENDATIONS

This paper has shown that the geotechnical understanding of the Ballina bypass project is enhanced considerably by developing of a detailed geological model. Within the package of sediments that make up the Quaternary deposits there are two distinct erosion surfaces that can be correlated across the whole site. The sediments between these surfaces have been characterised by their geotechnical properties, and an understanding of their spatial distribution can be considerably enhanced by correlating them with the geological model. The specific advantages are threefold. Firstly, by determining the depositional system that is being investigated (coastal estuary) and interpreting the geological history of the region, it is possible to understand the variation in geotechnical properties within similar, but age disparate, sediments (Gundarimba vs. Pimlico Clay). Secondly, it is possible to quantify the scale of particular surfaces (MZ1 and MZ2) and sedimentary packages and hence assess their impact on engineering structures. Finally, a geological model will highlight or suggest the existence of potential problem areas and may be used to target drilling to minimise cost and maximise the relevance of the data gathered.

Further work is required in order to understand the vertical and horizontal distribution of geotechnical properties of particular units within the depositional system, specifically, the Pimlico Clay. One area of interest is the possible occurrence of localised zones of sensitive clay. The depositional environments within an estuary vary, in both time and space, from hyper- to hypo-saline. These changes impact on the flocculation of suspended clay particles and subsequent microstructure after deposition. The estuarine regions are also periodically flushed with fresh water during flooding events and acidic water as a result of land clearing. This is likely to alter the pore-water chemistry of the deposited clay and result in changes in its sensitivity.

ACKNOWLEDGEMENTS

The financial support of the Australian Research Council in facilitating this research is acknowledged and appreciated. The assistance of the staff at Robert Carr and Associates, and The Roads and Traffic Authority of NSW in locating and accessing the data is also appreciated. I would also like to thank Stephen Fityus for his discussions and assistance in editing this paper.

REFERENCES

Bjerrum, L. (1967). "Engineering Geology of Norwegian normally-consolidated marine clays as related to settlements of buildings." Geotechnique **17**: 81-118.

Brierley, G. J., A. Brooks, et al. (1995). Floodplain Systems along the Coastal Plain of New South Wales, Geological Society of Australia.

Drury, L. W. (1982). Richmond River Valley Groundwater Investigation, Water Resources Commission N.S.W.: 90.

Drury, L. W. (1982). Richmond River Valley Groundwater Investigation. Sydney, Water Resources Commission.

Kenney, T. C. (1964). "Sea-level movements and the geological histories of the post-glacial marine soils at Boston, Nicolet, Ottawa and Oslo." Geotechnique **14**: 203-230.

McMinn, A. (1992). "Quaternary coastal evolution and vegetation history of Northern New South Wales, Australia, based on dinoflagellates and pollen." Quaternary Research **38**: 347-358.

Packham, G. H., Ed. (1969). The Geology of New South Wales, The Geological Society of Australia.

Pogson, D. J. and B. L. Hitchins (1973). New England 1:500,000. Sydney, Geological Survey of New South Wales.

Robert Carr & Associates, R. A. (2001). Draft report and site investigation for the Cumbalum and Teven Trial Embankments. Newcastle.

Robert Carr & Associates, R. A. (2003). Final Report: route investigation for the Ballina Bypass. Newcastle.

Roy, P. S. (1984). New South Wales Estuaries: Their origin and Evolution. Coastal Geomorphology in Australia. B. G. Thom. Sydney, Academic Press: 99-122.

Roy, P. S., J. P. Hudson, et al. (1995). Quaternary Geology of the Hunter Delta- An Estuarine Valley-Fill Case Study. Engineering geology of the Newcastle-Gosford region, Newcastle, Australia geomechanics Society.

Velde, B., Ed. (1995). Origin and Mineralogy of Clays: Clays and the Environment. Heidelburg, Springer.

Walker, A. (1999). Quaternary Sequence stratigraphy of the lower Hunter river valley. Geology. Newcastle, University of Newcastle: 216.