A review of geological models for east coast Australian estuaries

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ABSTRACT

The heavily developed and populated east coast of Australia consists of numerous short estuary systems that drain a narrow strip of continental margin east of the Great Dividing range. The sediment sequences that fill these estuaries pose many challenges to engineering development. This paper presents a brief review of a extensive body of literature that exists in fields such as sedimentology, geomorphology and coastal processes. This work is largely unknown by geotechnical engineers, but it offers insight and understanding that is invaluable in building geotechnical models for development in estuarine environments. It introduces the broad concepts of sequence stratigraphy and morphodynamics, and it demonstrates how cross-disciplinary concepts can be used to better understand the scale and distribution of estuarine soil deposits. Significant insights relate to the importance of temporal and physical boundary conditions, such as relative sea level changes and inherited geomorphology, in controlling the characteristics of deposited sedimentary sequences. The role of coastal barrier structures in limiting the scale of the different sedimentary environments, and hence deposits, is noted. The paper concludes by suggesting that the tools of sequence stratigraphy and morphodynamics can be used to evolve a geotechnical model during a geotechnical investigation. These tools can be to extrapolate the information gained from existing boreholes, to predict likely spatial trends, and guide the locations of subsequent boreholes, thus making the site investigation process more efficient and the final models, more reliable.

1 INTRODUCTION

A large proportion of the Australian population is concentrated along the east coast of Australia, living on and around coastal estuaries, each with its own set of physical, ecological and sociological characteristics. Commonly, and with increasing frequency, development is encroaching into estuarine areas, necessitating the formulation of geotechnical models to underpin good engineering practice. As many of the soil types that are characteristic of such environments are particularly problematic from an engineering perspective, the quality of the geotechnical model is all the more important.

The formulation of a geotechnical model, usually founded on some basic geological understanding, is commonly a simple and direct process, involving a number of generic steps, such as:

- Identify the areas of interest,
- Nominate an arrangement of site investigation locations from which to obtain data,
- Undertake a site investigation and conduct in situ testing,
- Analyse the data to identify principal soil units at each location,
- Interpolate between locations to produce a geological model,
- Characterise principal soil units using laboratory testing to produce a geotechnical model.

Whilst this approach usually results in satisfactory outcomes, it is not necessarily the most efficient. The features of geological models are often purely circumstantial, generally based on literal interpretation of the factual data, and employing little or no insight into the broader context of the geological environment in which the investigation is located.

This paper presents a brief review of an extensive body of literature that exists in fields such as geology, sedimentology, geomorphology and coastal processes, and that is mostly unknown by geotechnical engineers, but which offers insight and understanding that is invaluable in building geotechnical models for developments located in estuarine environments.

2 DEFINITION OF AN ESTUARY

In order to provide a starting point for the following discussion, a definition for an estuary is needed. Although many are possible, the definition by Dalrymple et al. (1992) is useful for the present purpose.

"An estuary is defined as the seaward portion of a drowned river valley system which receives sediment from both fluvial and marine sources, and which contains facies influenced by tide, wave and fluvial processes. The estuary is considered to extend from the landward limit of tidal facies at its head to the seaward limit of coastal facies at its mouth"

3 FORM AND PURPOSE

Human development on and around estuaries is not unique to Australia, and consequently, estuaries have been the subject of significant research world wide. As implied in the introduction to this paper, little of this research has been directed at the development of better methodologies for the formulation of improved geotechnical models. Motivations for research into estuarine environments include:

- A better understanding of the natural environment, and the processes that shape it,
- The conservation and management of estuaries as ecosystems, and/or as economic and social resources,
- Perceived threats from extreme climatic events or climate change (Carter and Woodroffe, 1992)

Accordingly, the usefulness of estuary studies to geotechnical engineering practice varies according to purpose of the research and the form it took. Few schemes have been developed solely on the basis of the structure of the subsurface deposits (the primary interest of geotechnical engineers) and so invariably, some adaptation of the information provided is necessary to make it useful in geotechnical modelling. In a review of classification schemes by Ryan et al. (2003), the basis for estuary classification includes climate, water quality, habitat types and extent, ecology, hydrology, morphology and physical measurements.

In many cases, the classification and analysis of estuaries according to the criteria listed above is made on the basis of surficial characteristics (eg hydrological, biological) of the estuaries at the present time (or over the geologically 'short' interval of human existence). Such studies are of limited use in geotechnical modelling. In some cases, however, largely confined to fields within the geosciences, classification and analysis is based on surface morphology, which is in turn related to the underlying processes that shape this morphology in geological time. Indirectly at least, insight into subsurface structure and properties is contained within such approaches. Clearly, fields within geoscience, are likely to hold the greatest potential benefit for geotechnical engineers.

In the consideration of estuaries by geoscientists, understanding seems to have developed on the basis of two principal perspectives: that the stratigraphy of estuarine deposits is formed by a sequence of events that occur (to greater or lesser extents) as a function of time; and, that estuaries are shaped by the dynamic processes that occur in response to the interaction between particular conditions and structures that prevail at any given time throughout its evolution (Carter and Woodroffe, 1992). These approaches are not mutually exclusive, but lead to different perspectives of the same phenomena. Hence, in a suitably adapted combination, they can provide valuable insights into the form and characteristics of estuarine deposits.

The remainder of this paper will provide a brief discussion of the potential usefulness of two estuary models: one based on sequence stratigraphy and the other based on morphodynamics.

4 SEQUENCE STRATIGRAPHY

Sequence stratigraphy (SS) is a complex, but powerful concept that has a particular usefulness for the grouping of similar sediments and the understanding of their possible spatial extent and relationships. The complexity of SS precludes a full discussion of its intricacies in the space available here, and the reader is referred to Miall (1996) for a more detailed discussion.

The basic premise of SS applied to estuaries is that an estuary is formed through cycles of valley incision followed by valley infilling, in response to falls and rises in relative sea level. It considers that the incised valley that exists at relative sea level lowstand is filled in a predictable way during sea level rises, so that there is a particular order in the resulting sequence of sediments in the filled valley. By definition, a sequence is that body of sediment that accumulates between two successive episodes of relative sea level highstand (maximum relative sea level).

The order within the sequence arises from the balance that arises between tidal flows and fluvial flows within the system. At any stage of the sea level cycle, a particular arrangement of physical environments exists within the estuary, determined by the distance from the mouth of the estuary at that time. These include the conditions described in the following points.

- On the ocean-side of the mouth, conditions are exclusively marine. Beyond the bar, predominantly fine sediments (marine muds) are deposited in relatively deep-water, saline conditions, forming a submerged ramp/fan structure.
- Throughout the estuary, conditions are tidal. In the mouth of the estuary (which is often constrained by the development of a sand barrier) and in the more constrained (usually upper) reaches of the estuary, channellised flows transport coarser sediments to or from the ocean, depending upon the relatively magnitudes of flow and energy in the system. In the wider reaches, these sediments are deposited as delta deposits
- Behind the barrier, estuaries usually broaden to form a central basin. The influence of tidal energy decreases, and fine sediment is deposited in the brackish, deeper-water, lower-energy conditions that predominate during much of the infilling process.
- At the margins of the estuary, tidal flat conditions, possibly hosting mangrove forests, are characterised by diurnal cycles of inundation and exposure as the tide rises and falls.
- Beyond the upper tidal limit, the prevailing conditions are exclusively freshwater/fluvial.

Such zones exist at any time, across the surface of the estuary, as shown in the general arrangement of Figure 1a, and as can be observed in many of the estuaries along the east coast of Australia. The potential benefit of a SS interpretation arises from the understanding of how these environments vary over time, as sea level rises and the valley fills. SS takes the general arrangement of Figure 1a, and integrates it with respect to time, as the zones of different depositional conditions morph (both vertically and laterally) in response to the relative position of sea level. A representation of the sedimentary sequence so formed is shown in Figure 1b.

Figure 1b indicates that sediment which accumulates under a given set of conditions will form geological units that have a predictable arrangement with respect to other units within the sequence. It also indicates that although a particular sedimentary unit should have relatively consistent physical properties, as determined by the conditions under which it formed, it may vary significantly in age throughout both its vertical and lateral extents.

SS make particular use of process transitions that occur throughout the sea-level change cycle. Transitions, such as from erosion to deposition, or from exposure to inundation, form identifiable surfaces within the sedimentary sequence. Once identified, these surfaces can indicate relative positions within the sequence, and give an indication of what kind of sediment units are likely to exist above and below that depth. Further, the sedimentary characteristics of each of soil deposits formed in each of the depositional environments is restricted, and in some cases, unique. Thus, the characteristics of sediments encountered during a site investigation can be used to allocate particular sediment bodies to the different sedimentary environments described above. This is useful for two reasons. Firstly, it allows the unit to be positioned within the generalised SS model, providing some constraint on the likely physical form and spatial extent of the unit. Secondly, knowledge of the conditions and processes under which the unit was formed essentially provides a geochemical and geomechanical history for the soil, giving insight into its likely engineering properties. Further development of these ideas is beyond the scope of this paper, and readers are referred to Bishop and Fityus (2006a) and Bishop and Fityus (2000b) for more detailed discussions.

5 MORPHODYNAMICS

While SS can provide great insights into the structure of estuarine sequences and the likely physical properties of the soils they contain, it is inadequate for geotechnical purposes in a number of respects. Most significantly, it is a generalisation, which is not readily adapted to all estuaries.

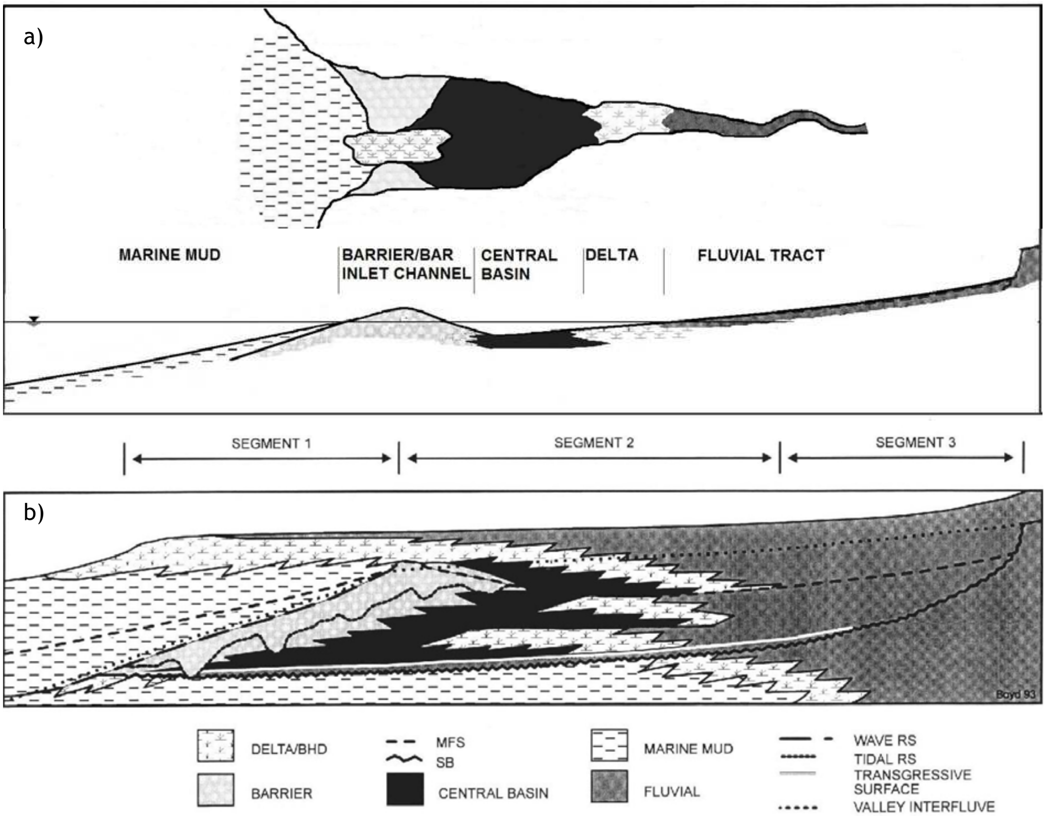


Figure 1 Sequence stratigraphic model of an incised valley estuary.
a) plan and eleveation of an estuary at an arbitrary sea level, during valley filling.
b) the sedimentary units formed by the integration over time, of the depositional zones in a), throughout a cycle of sea level change (after Dalrymple et al 1994)

While it works well for simple geomorphological arrangements such as that shown in Figure 1a, it is not so readily applied to estuaries of complex form, where for example, the incised valley has many branches/tributaries, with widely varying physical and hydrological characteristics. Even for the simple linear estuary arrangement of Figure 1a, while the arrangement of units in Figure 1b is typical, their length, width, thickness and continuity will vary depending upon many factors. Insights into these aspects of estuarine sequences is available from the field of morphodynamics.

Morphodynamics is an approach to estuary modelling that considers the form and arrangement of sediment deposits as a function of the processes that formed them. Coastal morphodynamics is defined by Wright and Thom (1977) as "the mutual adjustment of topography and fluid dynamics involving sediment transport." According to Carter and Woodroffe (1994), "the morphodynamic approach relies upon the predictability along certain environmental gradients, such as tidal range, wave exposure and sediment type" and is deterministic. They recognise that the behaviour of coastlines (of which estuaries are a component) is determined by many factors including geological structures, tectonic setting, sediment type and availability, sea level position, wave and current processes, and they conclude that the morphodynamics of coastal systems involve the complex mutual co-adjustment of processes and forms.

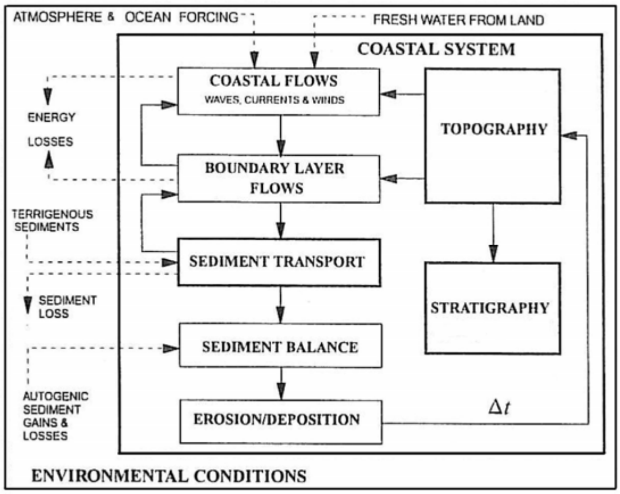
In studies of coastal morphodynamics, Carter and Woodroffe (1994) suggest that three factors are particularly important in most situations. These are

- The role of relative sea level change, which in the case of an estuary determines the area and volume of inundation as a function of time, and the rate with which these change.
- The sediment supply, which in the case of an estuary includes the sediment carried into the estuary by incoming tides, and the sediment delivered to the estuary by the fluvial system.

- The geological inheritance, which affects the morphology of the incised valley, and in turn, the dynamics of the hydrological processes.

There is also a case for including a fourth factor, climate. Although the role of climate is implicit in the sediment supply, it also drives fluvial flows, which are not accounted for in the factors above.

The fundamental importance of these four factors can be seen in Figure 2a, which gives an indication of the complex interactions between process (erosion, deposition, transport and flow) and form (topography). It is important to note that the end product of this complex dynamic system is stratigraphy, and so, the value of morphodynamics to geotechnical model is explicitly shown.



taken from
Cowell and Thom (1994)

Figure 2. Diagram illustrating the complex mutual co-adjustment of processes and forms.

In the context of building geotechnical models for specific estuaries, morphodynamics can be used to help answer questions such as "is a particular branch of an estuary likely to be dominated by coarse (tidal delta) or fine (central, basin mud) sediments." To apply the principles of morphodynamics in a particular situation, it is necessary to have some specific information about the particular controlling factors. Essential amongst these are: information about past relative sea level changes; morphological data, of the present ground surface at least, but preferably of the base of the incised valley; data on the present and past tidal range; and data on the size and climate of the catchment (or catchments) feeding into the estuary, to account for the hydrological flows and sediment input from the fluvial system. A full, generalised framework for morphodynamics analysis is beyond the scope of this paper. However, as an illustration of how the principles of morphodynamics might be applied to geotechnical modelling, we will consider how it might be applied to the question posed above.

According to fundamental principles, large flows in confined channels result in high energy conditions, that shift loads of sand and preclude the sedimentation of finer silts and clays. Low flows in wide basins cannot carry sand loads, and allow fine sediments to settle. So, if a particular branch of an estuary is long and narrow, then it will accommodate large volumes of tidal flow, that will be constrained to a narrow channel. In this case, we expect that clay deposits will not be extensive, and that sand bodies will dominate throughout the tract. If the upstream catchment is small/low rainfall/low topographic relief, then we expect that the sand sediment will be dominated by marine sands carried upstream during tidal inflows. If the upstream catchment is large/steep/high rainfall, then we expect that it will be able to supply sufficient sediment that there will be a net sediment transfer to the ocean, and fluvial sands will dominate the sand bodies.

Consider now, a short, broad estuary, which behaves more as an embayment than a channel. The tidal exchange volume is small, and the sedimentary environment is low energy. If the catchment supplies little of its own sediment, then sedimentation of fine suspended sediment from other parts of the estuary into relatively deep water will be slow, and soft clays will dominate in the estuary. If the catchment produces significant sediment of its own, wedges of coarse fluvial sands will build out into the estuary, where the fluvial system meets the relatively still water of the estuary.

6 CONCLUSIONS

Sequence stratigraphy and morphodynamics are powerful conceptual models that provide insights into the structure and stratigraphy of estuarine deposits, that are not readily obtained from the simple plotting of cross sections, on the basis of a series of arbitrarily positioned boreholes. Using sequence stratigraphy, the position of characteristic boundary surfaces can be identified in a single borehole, placing constraints on possible estuary structure, and facilitating the postulation of an initial estuary model that can be used to guide the strategic positioning of subsequent boreholes. If the soil layers in a borehole at a particular position within the estuary can be interpreted in the context of, say, Figure 1b, then the likely changes in conditions upstream or downstream of that point are implied by the general trends shown in Figure 1b. Then, using morphodynamics, some idea of the likely extent of the sediment unit encountered in a borehole can be postulated, relative to the particular morphology of the estuary and its particular boundary conditions.

Sequence stratigraphy and morphodynamics are complicated conceptual models that cannot be adequately considered in a short conference paper. This paper demonstrates, however, that they hold great potential as tools to facilitate better geotechnical models in estuarine environments, and hopefully, it serves as incentive for the geotechnical profession to invest the time and effort to make greater use of them in routine practice.

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