

THE SENSITIVITY FRAMEWORK: BEHAVIOUR OF RICHMOND RIVER ESTUARINE CLAYS

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ABSTRACT

The stability and long-term settlement behaviour of NSW estuarine clays under load has become increasingly significant as a result of the large-scale infrastructure development currently occurring in coastal NSW.

The Structured Clay Framework (SCF) developed by a number of authors over the past 20 yrs (Burland *et al.*, 1996; Chandler, 2000; Cotecchia and Chandler, 2000) and based on the work of Burland (1990), provides a general framework for understanding the behaviour of natural structured clays. This is analogous to the framework for remoulded soils provided by Critical State Soil Mechanics (CSSM).

The basis of the SCF is a normalised void ratio vs. effective stress relationship generated from oedometer tests on remoulded clay. The parameters used in the normalisation procedure are the intrinsic properties of e_o^* , e_{100}^* and e_{1000}^* the void ratios of the remoulded clay at the liquid limit, (e_o), $\sigma'_{vo}=100\text{kPa}$, (σ'_{100} , e_{100}^*), and at $\sigma'_{vo}=1000\text{kPa}$ (σ'_{1000} , e_{1000}^*). The “intrinsic” properties represent the values of clay with no microstructure i.e. its baseline properties.

Unlike standard empirical correlations between geotechnical properties and Atterberg limits there is a rigorous analytical basis (i.e. CSSM) for these correlations (Burland, 1990). The behaviour of high quality undisturbed tests can then be compared and classified according to this intrinsic baseline. The SCF provides a quantitative measure of the structure component of the clays consolidation and shear behaviour above that predicted based purely on void ratio stress relationships (Burland, 1990).

The work presented in this paper describes the implementation of the SCF on Holocene estuarine clays from the Richmond River in Northern NSW. These geologically normally consolidated clays form a significant component of the foundations of the proposed Ballina Bypass and it has been noted, anecdotally, that a number of these clay deposits suffer from large (3 m under a 7 m embankment) settlements and have relatively high sensitivities (4-10, shear vane). Both these factors suggest micro-structure may play a significant role in the overall behaviour.

The initial results indicate that the SCF method provides a useful tool for relating mechanical behaviour, in terms of oedometer and shear vane results, to periods in the geological evolution of the estuarine deposits. Significantly, zones of high sensitivity clays, the deposition of which relates to a period of rapid flooding within the estuary, have been identified. They have much higher intrinsic values that can be accounted for under normal sedimentation conditions, suggesting that they are highly structured. This fact is not apparent when using the standard Atterberg correlations.

1 INTRODUCTION

The Critical State Soil Mechanics framework forms the basis of many of the soil models used in engineering practice. This framework is based on extensive testing on remoulded clays (Muir-Wood, 1990). However the behaviour of remoulded clay differs significantly from natural clays due to the presence of structure (Burland, 1990; Leroueil *et al.*, 1990a). This structure is a combination of the clay *fabric* or particle orientation that is imparted at the time of deposition, and the *stability* of this fabric resulting from electro- bio- and physiochemical bonds formed during and post-deposition. Subsequent void ratio changes due to burial consolidation do not alter this initial stability but improve the overall strength characteristics by increasing the degree of interparticle interaction. Together the *fabric* and fabric *stability* are defined as the *structure* of the sediment (Mitchell and Soga, 2005).

Both Terzaghi (1941) and Skempton (1970) investigated the Sedimentary Compression Curves (SCC) of normally consolidated marine sediments under gravitational loading. They showed that a log linear relationship exists between the void ratio and *in situ* effective stress, but also that, for a given void ratio, a gravitationally loaded soil will carry an *in situ* effective stress approximately 5 times higher than the equivalent remoulded clay. This difference is a measure of the enhanced deformation resistance of the natural clay fabric over the remoulded clay fabric.

It is generally assumed that the soil's *structure* evolves during burial and adjusts so that it will just support the overlying load, i.e. the soil is normally consolidated and the oedometer will detect the geological preconsolidation pressure. However for many recent normally consolidated clays the structure that forms as a result of the deposition process and post-depositional phenomena results in the soil's fabric attaining a degree of *stability* above that required to carry the

overburden load. These processes include bioturbation, thixotropy and precipitation of cements (Leroueil and Vaughan, 1990; Schmertmann, 1991). This extra structure will result in an increase in the soil's sensitivity, where the sensitivity (S_s) is defined as the ratio of undisturbed strength (S_u) of the clay to the strength of a fully remoulded sample ($S_{u, remoulded}$). By definition, remoulded soils have a strength sensitivity of 1 (Mitchell and Soga, 2005). This *structure* should be considered as important as the *in situ* void ratio and stress history in defining the soils behaviour (Leroueil and Vaughan, 1990).

The problem in modelling or predicting the geomechanical behaviour of structured natural clay is that many of the behaviours observed are not predicted by the CSSM framework (Burland, 1990). The central tenant of CSSM is the direct link between void ratio, peak strength and effective stress (Muir-Wood, 1990). This relationship divides soil behaviour into two zones. Below the peak strength, or yield state, soils behave elastically and pore pressures rise uniformly in proportion to the applied load. At stresses above this peak state, soils behave in a plastic manner and plastic deformation results in the expansion of the soil's "yield surface" and improvement in its strength characteristics. The presence of *structural stability*, above that defined by the void ratio and *in situ* stress conditions in a ground, means that a soil can exist in a state outside the yield envelope predicted by CSSM. In other words the clay fabric is metastable (Mitchell and Soga, 2005).

It is important to realise that dramatic increases in clay sensitivity after burial occur due to a reduction in the remoulded strength of a soil rather than an increase in the undisturbed strength (Mitchell and Soga, 2005). A process that can cause this is a reduction of pore water salinity in marine sediments due to fresh water flushing (Torrance, 1975) This process plays an important role in the formation of the quick clays in Northern Europe (Bjerrum, 1967) and the highly sensitive Champlain Sea Clays in Canada (Leroueil *et al.*, 2003). The behaviour of these soils is considered unusual because their metastable fabric has a tendency to collapse (Cotecchia and Chandler, 2000) resulting in significant and dramatic pore pressure development (Hoeg *et al.*, 1969). Hoeg *et al.* (1969) noted that during embankment loading the excess pore pressure generated was significantly lower than expected below a critical embankment height ($\Delta u/\sigma_{vo} = 15-20\%$ predicted). Once this critical embankment load was reached (approximately equivalent to σ'_{vy}) the rate of excess pore pressure increased dramatically and continued to rise significantly up to a week after loading was complete. Another aspect of sensitive and quick clay behaviour is that at low confining stresses (Burland, 1990) and rapid strain rates (Leroueil and Hight, 2003) these soil have a tendency to behave in a brittle manner.

An important consequence of structure and sensitivity in soils is the fact that their behaviour cannot be described by CSSM. The CSSM framework is not able to predict the peak undrained shear strength, S_u , of normally consolidated sensitive clays, because this strength is a function of *structure* not the maximum *in situ* stress condition the profile has experienced. There are also significant implications for behaviour predictions using continuum models based on CSSM, since the observed brittle behaviour results from strain localisation and this cannot be modelled using continuum mechanics methods (Hight, 2006).

What appears to be poorly appreciated within the Australian geotechnical community is what constitutes sensitive soils and the possibility that they may be as prevalent in Australia as they are in northern European and Canadian deposits. Clays of high *in situ* sensitivities ($S_{u \text{ vane peak}}/S_{u \text{ vane residual}}$) in the region of 8-24 have been recorded in the Richmond River Estuary in Northern NSW. On a world scale, these are considered very sensitive to slightly quick soils (Mitchell and Soga, 2005).

The research presented in this paper applies the concept of the sensitivity framework in order to demonstrate the important role played by soil structure in controlling the geomechanical behaviour of east coast Australian estuarine clays.

2 SENSITIVITY FRAMEWORK

This section briefly reviews the concept of intrinsic parameters proposed by Burland (1990) and the sensitivity framework developed by Cotecchia and Chandler (2000), based on the use of intrinsic parameters. The sensitivity framework provides a semi-quantitative understanding of the degree of *structure* in a natural soil through a comparison of its natural behaviour to a baseline of its remoulded clay behaviour. The sensitivity framework is a behavioural framework for natural clays akin to CSSM for remoulded clays.

By remoulding a soil at a moisture content of between 1.25 and 1.5 times its liquid limit any natural structure is considered to be removed. The geomechanical properties of a soil reconstituted in this way are defined as its intrinsic properties (Burland, 1990). As in Burland (1990) the intrinsic properties presented here are denoted with an asterisk, *.

The intrinsic parameters are derived from a standard incremental oedometer test on the remoulded soil. The intrinsic compression index, C^*_c , is defined as the difference between the void ratio at 100kPa (e^*_{100}) and the void ratio at

1000kPa (e^*_{1000}) of the fully remoulded material. These values are represented schematically in Figure 1(a) for two remoulded clays of with different index properties. The values e^*_{100} and e^*_{1000} are determined directly from the curves.

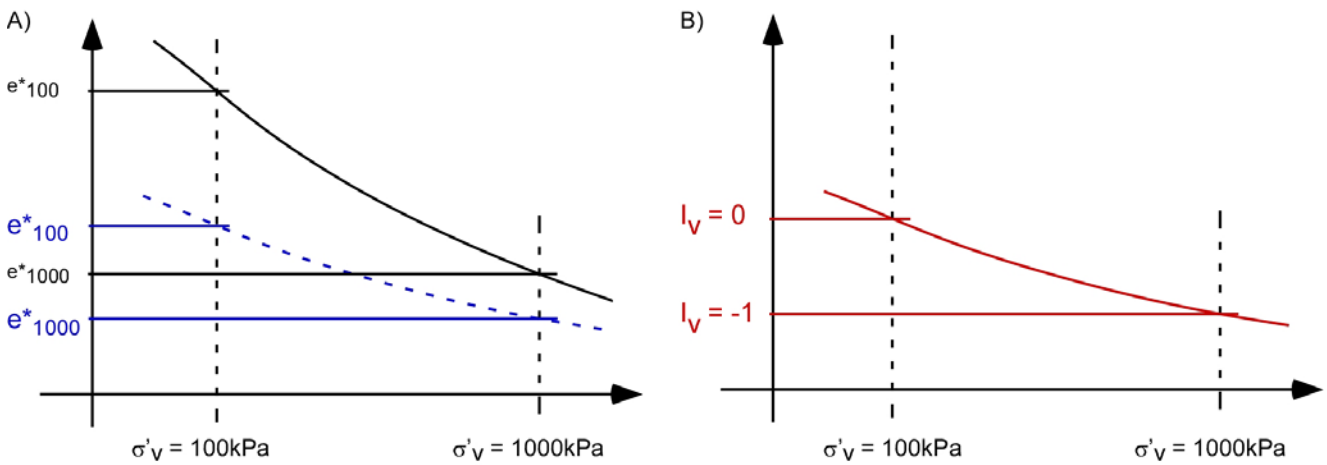


Figure 1: Derivation of the Intrinsic clay parameters (a) Oedometer curves of two remoulded clays with different LL (b) Same curves, normalised using intrinsic properties to produce the Intrinsic Compression Line.

The parameter, C^*_c , is used to normalise the particular e vs. $\log \sigma'_v$ curve according to Equation (1). The resulting normalised value is defined the void index, I_v , and when plotted against σ'_v both curves fall onto a single curve as shown in Figure 1(b). This curve is defined as the Intrinsic Compression Line or ICL.

$$I_v = \frac{e - e^*_{100}}{C^*_c} \tag{1}$$

A similar normalising effect can be achieved using the Liquidity Index as was demonstrated by Skempton (1970) for a range of natural clays. However, the Void Index is considered by a number of authors (Chandler, 2004; Hight and Leroueil, 2003) as a more rigorous basis for comparison of soil behaviour because it incorporates an explicit link between void ratio, stress and clay behaviour in the oedometer test, rather than the implicit relationship between plasticity and geotechnical properties represented by the Liquidity Index.

Burland(1990) proposed a second reference line within the intrinsic framework termed the Sedimentary Compression Line (SCL). This line is derived using the Void Index and Skempton's original data for normally consolidated clays (Skempton, 1970). The SCL and the ICL are approximately parallel, so that the ratio of stresses at a given void ratio is around 5 (Burland, 1990), as shown in Figure 2.

Within this framework, it is possible to compare the degree of structure in the clay being studied relative to both its intrinsic values and against the average line (SCL) of clays whose structure is purely a function of gravitational loading. The *in situ* state of the soil is defined by the *in situ* stress, σ'_{vo} and the *in situ* void ratio e_0 . In this discussion the term σ'_{vc} will be used to define the past maximum *in situ* stress determined from the geological loading history. The oedometer curve for a normally consolidated¹ clay ($OCR=1$, $\sigma'_{vo} = \sigma'_{vc}$) that has a degree of structural resistance above that defined by the maximum *in situ* stress (i.e. 'metastable') will display the behaviour shown in Figure 2(a). The soil will have a yield stress, σ'_{vy} , greater than the *in situ* stress σ'_{vo} . The ratio of these two stresses, $\sigma'_{vy}/\sigma'_{vo}$, is termed the yield stress ratio or YSR (Burland, 1990). A measure of the available structural resistance above the ICL is provided by the ratio of the yield stress to the intrinsic stress, $\sigma'_{vy}/\sigma'_{ve}^*$, called the Stress Sensitivity or S_σ (Cotecchia and Chandler, 2000).

The black oedometer curve in Figure 2(b) represents the behaviour of an over consolidated clay with no structural sensitivity (YSR =1). The curve approaches the SCL and begins to deflect at the point equivalent to the past maximum stress ($\sigma'_{vy} = \sigma'_{vc}$). The term yield (Chandler, 2004) or gross yield (Hight and Leroueil, 2003) is used to describe this point within an oedometer test. The idea of yielding may seem unusual in the context of the oedometer however it is actually appropriate in that it represents the onset of plastic deformations within the soil skeleton (Leroueil and Vaughan, 1990).

¹ In this discussion, reference to over consolidation ratio and preconsolidation pressure relate strictly to values based on the gravitational loading history of the clay, rather than inferred from the oedometer test results.

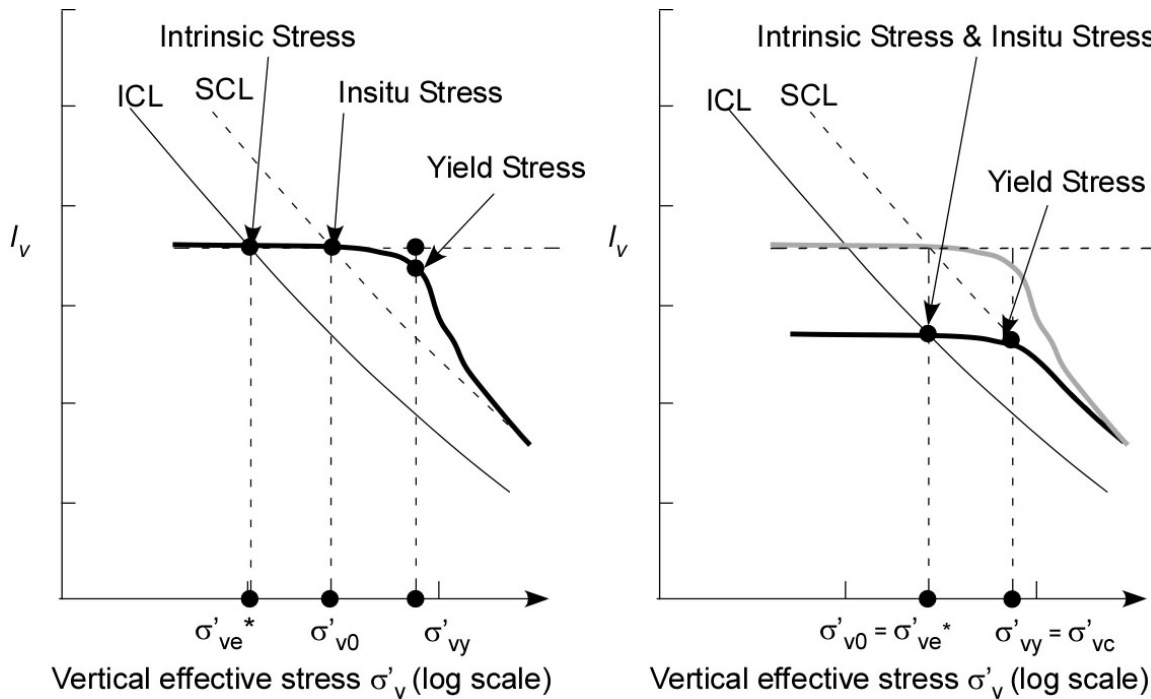


Figure 2: Sensitivity framework for oedometer curves of 2 clays (a) a normally consolidated clay with structure and (b) an over consolidated clay with only gravitational structure.

The most important distinction between the two clays represented in Figure 2 is in the post-yield behaviour. With the presence of structure, the clay in a) exists outside its limit state curve. Once this structure has been broken down the limit state curve will shrink, rather than expand as predicted by CSSM. There will be a decrease in the subsequent measured stiffness, peak shear strength and preconsolidation pressure. The pore pressure response of the post-yield clay will also be significantly different. Behaviour during yielding will also be different, the most significant variation being the pore pressure response. Since the structured clay is undergoing significantly greater plastic deformation in returning towards the SCL, the excess pore pressure will be higher than predicted for clay that was normally consolidated. As was described in the introduction these pore pressure responses are characteristic of the sensitive clays of Canada and the quick clays of Norway. A more important implication of a high degree of structure in a normally consolidated material is the fact that this clay has a greater tendency to deform in a brittle manner at low confining stresses (Burland, 1990) or higher strain rates (Leroueil and Hight, 2003). This has significant ramifications for the prediction of behaviours during embankment construction to end of primary settlement using continuum models based on CSSM.

As a substitute for detailed geological information, the oedometric yield stress (σ'_{vy}) is sometimes considered to represent the past maximum gravitational load (σ'_{vc}). It can be seen from Figure 2 that this assumption would lead to the prediction of the same over consolidation ratio for both clay samples in Figure 2(b). In turn, the structured, normally consolidated clay (grey curve in Figure 2b) could be mistaken for having the behavioural properties of the over consolidated material (black curve). The initial stiffness measured by the initial reload slope in the oedometer curve, may be taken as the recompression index of an over consolidated clay, when in fact this slope may represent the structural stability of a sensitive clay material.

The remainder of this paper will consider the results of oedometer tests conducted on soft soils from the Richmond River Estuary. A detailed geological history has been developed for this deposit (Bishop, 2006) that allows a comparison of the behaviours within the Sensitivity Framework.

3 RICHMOND RIVER: SITE CHARACTERISTICS

The lower Richmond River flows across a low floodplain (around 2 m AHD) that caps a mature (Roy *et al.*, 2001) Holocene barrier-estuary fill sequence (Figure 2a). The sand barrier is shore parallel and extends between the rocky headlands of Evans Head to the south and Ballina to the north. This elongate, shore parallel barrier and back-barrier fill pattern is typical of the northern estuaries along the east coast of Australia (Roy, 1984). Below the 1 m thick floodplain deposits, the barrier-estuary sediments consist of a tidal delta sand system, a large area of central basin clays and silts, dominated by black shelly clays with considerable authigenic sulphides and coarse (silt-sand-fine gravel) fluvial delta deposits buried within the Emigrant and Duck Creek tributaries (Figure 3). The current tidal delta system is confined to

the main Richmond river and North creek channels but behind this, under the Ballina Township, is an extensive early-Holocene tidal sand delta (Figure 3). The fluvial deltas are confined to narrow bedrock-controlled tributary valleys (Macquires, Emigrant and North creeks). The central basin clays and silts range in thickness from 8 m to 25 m and underlie much of the current floodplain. They become thinner towards hills on the eastern margins of the floodplain and peter-out on the barrier sands.

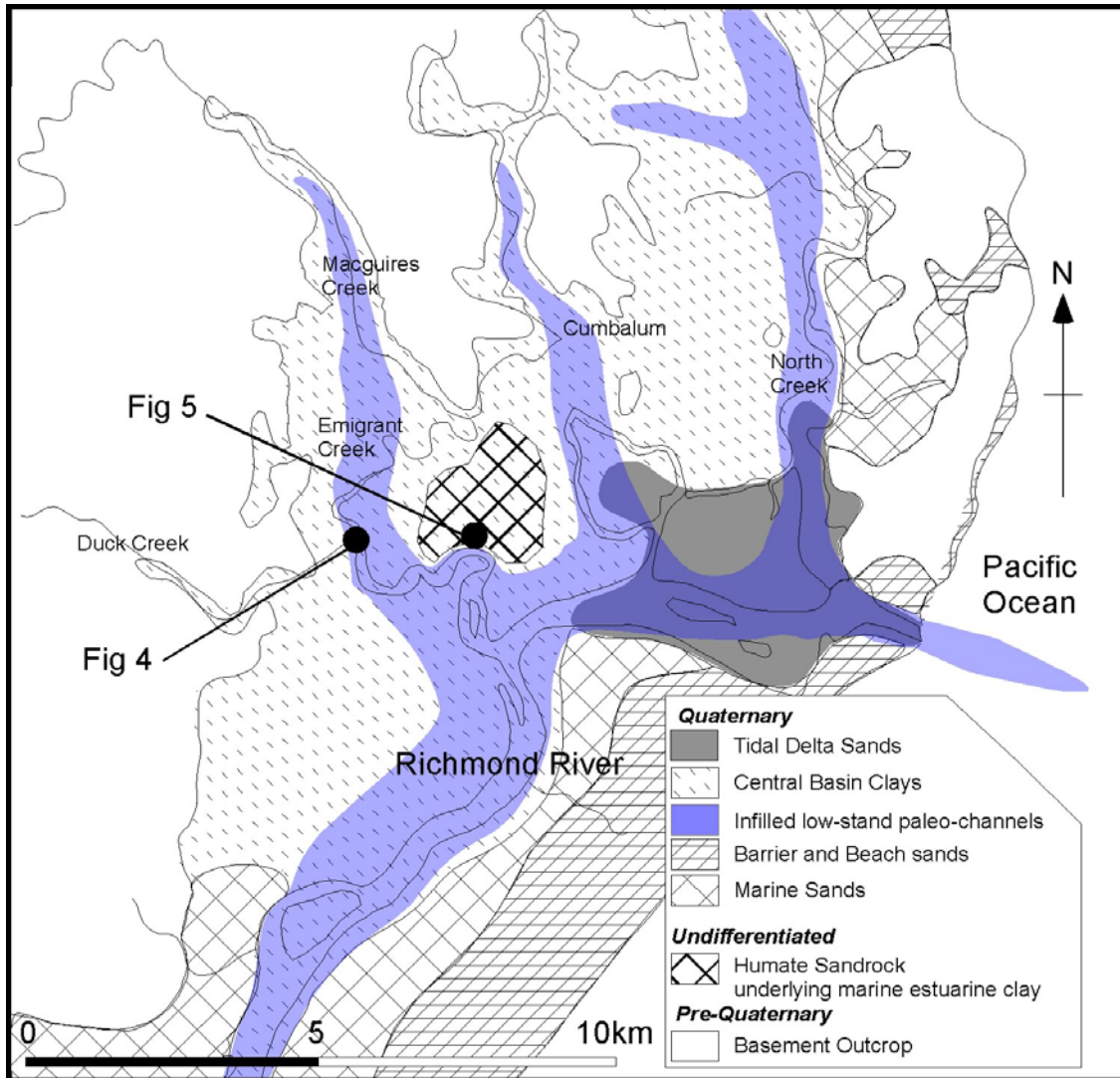


Figure 3: Map of Richmond River mouth with locations of Cumbalum and Teven and section.

The Holocene-Pleistocene sequence boundary defines the base of the Holocene estuary sediment. This boundary consists of a number of paleochannels carved into Pleistocene estuary deposits from the last highstand (120,000yrs BP) and possibly earlier highstand estuary deposits (Drury, 1982a). The paleochannels define the thalweg of the drainage system that would have existed at sea level lowstand around 18,000yrs BP. The channels are separated by interfluves that define terraces of stiffer sediments within the soft Holocene sediments. These terraces define the areas of thinner deposits of central basin mud.

The basement rocks consist of highly deformed interbedded metasediments of the Lower Proterozoic Neranleigh-Fernvale group (Packham, 1969). These rocks are overlain by Tertiary Volcanics of the Lamington Group (Packham, 1969). The basalts, rhyolites and tuffs belonging to this group dominate the outcrops that form the hills and headlands in the Ballina Study area (Figure 3) exposures. It is these rocks that are the dominant source material for the non-marine component of the estuary sediments.

The evolution of the coastal Richmond deposits has been defined by cycles of sea level rise and fall since the early Pleistocene. The presence of large amounts of humate sand rock (locally known as coffee rock) formed by the precipitation of humate substances from the groundwater flows is responsible from the preservation of older sediments. It also forms the substratum for the aggradation of the coastal sand barrier at a similar location during repeated sea level

highstands. The dominant depositional environment behind the barrier during highstand is the central basin: a brackish tidal mud and mangrove system (Hashimoto *et al.*, 2006). interspersed with tidal channels containing marine sand deposits (Bishop 2004). Areas of this system evolved under anaerobic conditions resulting in extensive post depositional alteration of the clays and formation of secondary sulphides and carbonates. A recent sea level fall of around 1m since 3000yrs BP (Goodwin *et al.*, 2005) has seen the incision of the main drainage channels into the marine clays of the central basin. This has resulted in the formation of meander and point bar organic deposits as the river adjusted to the new flow conditions.

4 INTRINSIC BEHAVIOUR OF ESTUARY CLAYS

Sample disturbance has major implications for values interpreted from laboratory testing. Current standard practice of testing U75 tube samples in Australia does match that used in Northern Hemisphere projects. Extensive research has shown sensitive material sampled using U75 samples will cause excessive sample disturbance (Jamiołkowski *et al.*, 1985) and interpreted oedometer results may underpredict the actual preconsolidation pressures by as much as 30% (Leroueil, 1996). Although the utmost care was taken with the samples during testing, this degree of disturbance must still be expected, even with the U100 sampling methods used. The oedometer yield stresses have been interpreted using Casagrande construction. Adjustments for the *in situ* conditions were also made according to the recommendations of Terzaghi *et al.* (1996). In order to obtain the actual yield stress accounting for sample disturbance, this value was adjusted by 30% in line with the values determine by Leroueil (1996) from oedometer tests conducted on samples obtained from high quality block samples compared to U75 samples. Importantly though, the sampling process only acts to reduce the peak values, so if high levels of *structure* are identified they are likely to be, if anything, lower bounds to the true values. That is, increased care in sampling will only reveal higher levels of structure still. It is important to remember that by normalising the oedometer data in the manner described in the previous section, the effects of soil composition and plasticity are removed and the clays are being compared on an equivalent basis.

Two methods for determining the intrinsic parameters are possible. The first and preferable method is to obtain the values from tests on the remoulded material. With regards to the data presented in this paper intrinsic tests have only been conducted on the floodplain clay, Figure 4a. The plot of this ICL is shown in Figures 4a and 4b (dashed blue line). Over the range of pressures, 10-1200 kPa, there is excellent agreement with the literature values as shown by relative positions of ICL (green and brown) and SCL (blue) reference lines from Burland (1990) and Chandler (2000). The deviation below 10 kPa is most likely to be due to restructuring that has occurred during the preparation of the reconstituted material. The second method for determining e^*_{100} and C^*_c is to use the correlation equations determined by Burland (1990). These equations relate the Index properties of the clay to its intrinsic values (see appendix). This method has been used to derive the intrinsic oedometer curves for the samples in Figure 4b and Figure 5.

One of the proposed uses of the sensitivity framework is in detecting variations in depositional environment (Chandler, 2000). In the conditions envisaged during the evolution of the Richmond Estuary (and other east coast Australian estuaries) some clay deposits will have evolved in shallow tidal flat environments while adjacent clays have evolved entirely in the deeper water within the open water portion of the central basin. The data in Figure 4 is derived from oedometer tests performed on two samples of grey shelly clay from different depths within the sample borehole (Figure 3). The sample in Figure 4a is of from 3.15 m below ground surface ($w_n=74\%$, $w_L=89\%$, $PI=56\%$). The sample in Figure 4b is from 4.75m below ground surface in the same location ($w_n=107\%$, $w_L=118\%$, $PI=83\%$). The shallower clay (Figure 4a) lies to the left of the ICL while the deeper clay (Figure 4b) lies significantly to the right of the SCL. The deeper clay also has a more open yet just as stable structure, indicated by the higher void index but similar yield strength. The *in situ* stress conditions are only marginally different and, since both clays are normally consolidated from a geological perspective (Bishop, 2006), the difference is indicative of different depositional conditions. Within this framework, normally consolidated clays deposited in a tidal flat environment will plot on or to the left of the ICL (Chandler, 2000). This is due to the diurnal flooding they are subject to and, although they not become desiccated when aerially exposed, they are subject to negative pore water stresses during low tide periods. As a result, the structure that they evolve is more stable than deeper water sediments. The importance of this from a geological perspective is that once a particular clay environment becomes buried (e.g. during rising sea levels) the relative position of the *in situ* state to the ICL and SCL will remain fixed and the void index will evolve parallel to these lines.

The slope of the swelling path of the undisturbed sample compared to the remoulded sample in Figure 4b demonstrates an important element of the structure (Burland, 1990). The influence of the structure in the sample is to increase the ability of the sample to rebound relative to its remoulded counterpart. In this case it indicates that complete structural breakdown has not occurred through the first stage of the oedometer test. It is also apparent that there is a clear difference between the slope of the initial loading line compared to the reload line. This is further evidence of the degree of structural breakdown that occurs during primary consolidation of the undisturbed sample.

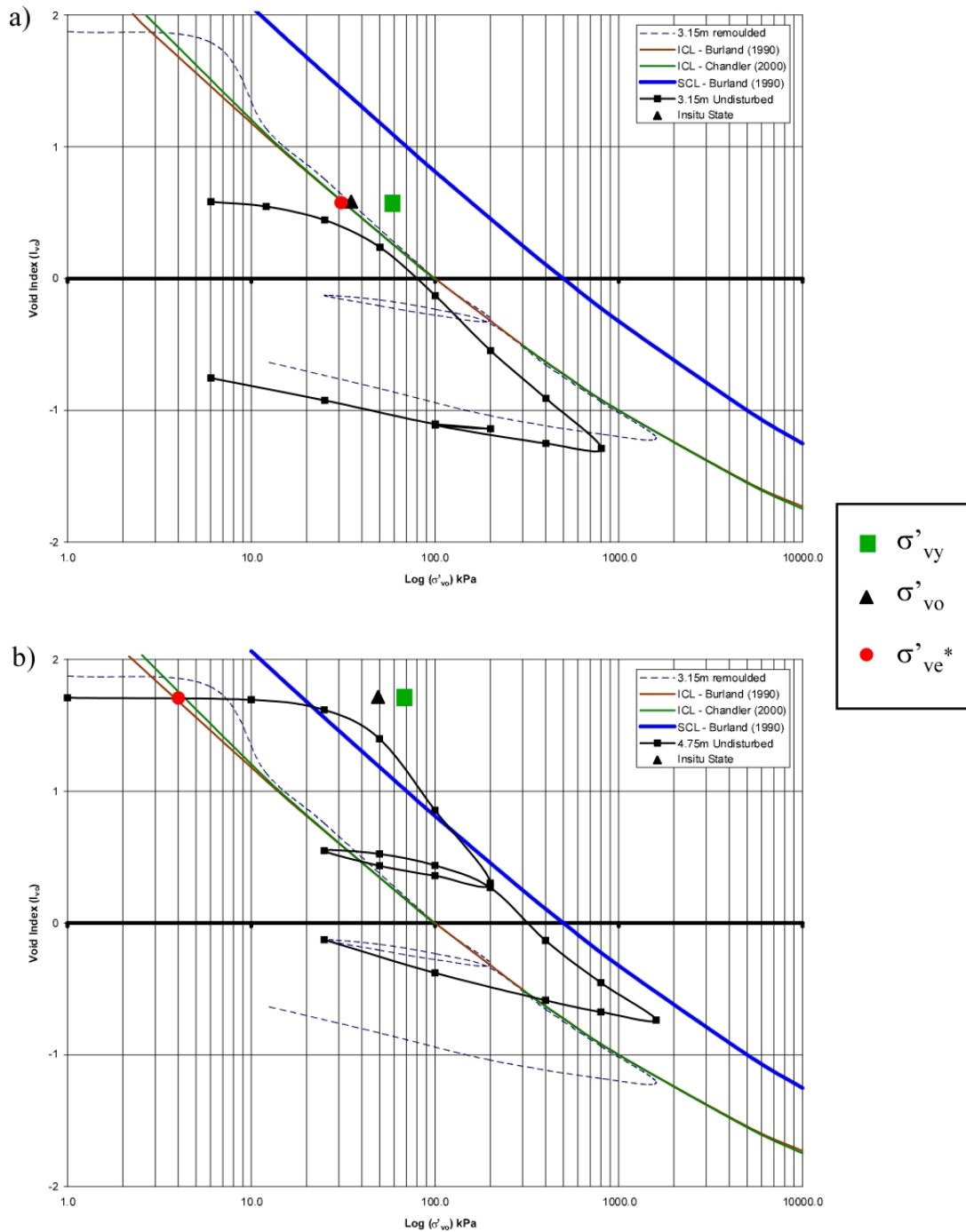


Figure 4: Intrinsic oedometer curves for samples from Bruxner (a) Central Basin Clay and (b) Floodplain clays.

Figure 5 shows the intrinsic oedometer plots for two clays from within a single profile (refer to Figure 3). The presence of a humate sand rock layer (Figure 3) separating the clays indicates that the lower clay is Pleistocene in age (Roy, 1984). The upper clay (4.2 m depth) is Holocene and has similar index properties to the Central basin Clay from Figure 4b. The lower clay has a natural water content of 60%, a liquid limit of 60% and a plasticity index of 37%. Both clays lie to the right of the ICL indicating a significant level of structure in both, however the lower clay lies on or just to the right of the SCL. In terms of deposition environments both clays were deposited in deeper water brackish marine conditions, evidenced by the presence of small quantities of shell hash and almost no sand. Both clays have natural water contents near their liquid limits and if they had been deposited in a continuous sequence they would both lie a similar distance to the right of the SCL. The fact that they do not supports the conclusion that the lower clay is Pleistocene. Sea levels at the time of deposition of the lower clay (112,000yrs BP) were approximately 5 m higher than present day conditions. This would imply an approximate additional overburden stress of at least 70 kPa (assuming 5 m extra marine clay at $\gamma_{bulk} = 14 \text{ kN/m}^3$) that has since been removed. Stress of at least this magnitude is recorded in the

distance between the *in situ* condition σ'_{vo} and the yield stress σ'_{vy} . Since the lower clay is now under a lower overburden stress its *in situ* condition is shifted to the left. The upper clay, which is normally consolidated has a degree of structure that allows it to exist at a void index (read void ratio) and stress state (σ'_{vo}) well above the value that it should begin to collapse (σ'_{ve^*}). Both clays undergo significant structural yielding during loading recognised by the fact that the slope of the loading curve is significantly steeper than the intrinsic and sedimentary curves.

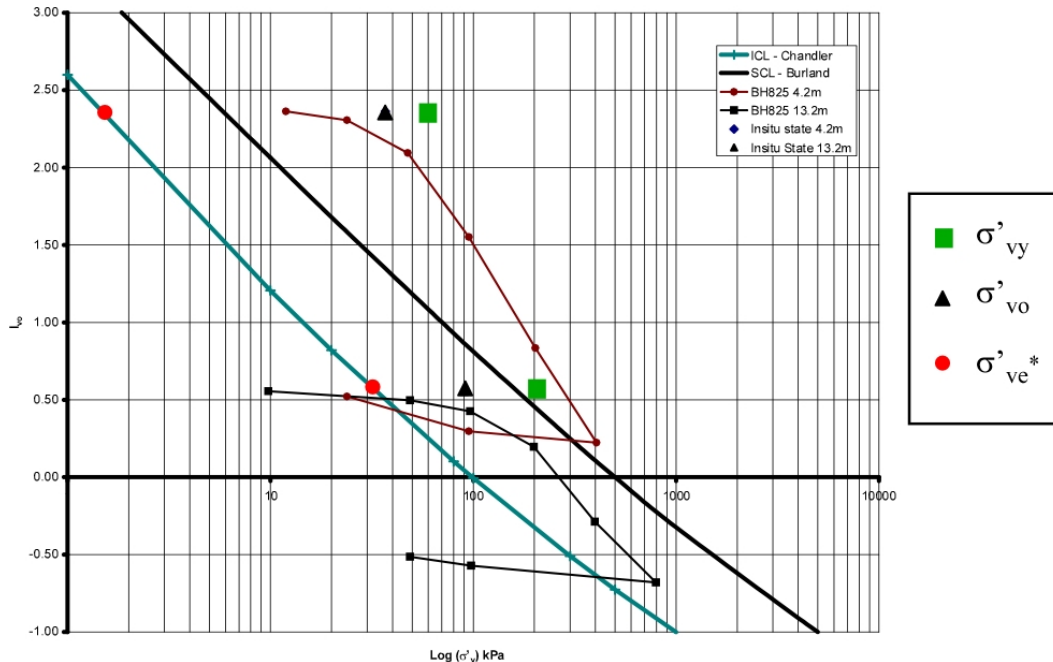


Figure 5: Intrinsic oedometer curves for a) Holocene Central Basin Clay (4.2m) b) Pleistocene Central Basin Clay (13.2m) both samples are from the same borehole (Figure 3).

5 SENSITIVE CLAYS IN NSW ESTUARIES

The important question to consider in this section is whether sensitive soils exist in Australia.

In order to examine this it is necessary to qualify both the definition of sensitivity and the scale used to quantify the sensitivity. The data set of *in situ* vane results with both peak and remoulded values is quite considerable for the Richmond region so this data will be used in conjunction with the oedometer results. Table 1 presents the Sensitivity Framework ratios defined previously in Section 3. These are the Yield Stress Ratio (YSR) and the Stress Sensitivity, S_σ . The *in situ* shear vane sensitivity (S_{rvane}) for the tested clays are given on the right of Table 1. Also included in this table are equivalent data from a deposit of sensitive marine clay from Onsøy in Norway. The data for the Onsøy clay was obtained from Lunne *et al.* (2003). Most importantly this is the same clay investigated by Bjerrum (1967) in his landmark paper investigating the behaviour and formation of the Drammen River quick clays.

Firstly, on the scale of shear vane sensitivities proposed by Rosenqvist (1953) values in the region of 6-8 are considered very sensitive. It is immediately apparent that these sensitivities are found in the Richmond clays (Samples highlighted by Bold type). Comparable stress sensitivities (S_σ) also occur in this material but it is interesting to note that some samples with high stress sensitivities do not have high shear vane sensitivities (BH825 4.2 m). This reflects the fact that although a soil may have an open structure signified by the high values of S_σ its remoulded strength can also be high thus reducing the measured sensitivity.

The behaviour of the clays in the oedometer and the values presented in Table 1 indicate that highly sensitive clays do occur and are common within the Richmond Estuary. The published data on Australian estuarine clays is very limited and few of the behaviours that characterise high sensitivity clays have been officially reported. It is highly likely that this is due to the nature of the projects which have been undertaken on the estuaries. Predominantly these projects have been large embankments for transport infrastructure in which issues of stability, even on sensitive materials, can be designed for (Leroueil *et al.*, 1990b). The absence of projects in which stability is an issue means that the performance of these soils under critical conditions has not yet been tested.

Table 1: Intrinsic parameters and sensitivities for clays in the Richmond compared to Onsøy Clay (Norway), values in brackets are the values uncorrected for sample disturbance

Sample	Deposition Environment	σ'_{vy} (kPa)	σ'_{vo} (kPa)	YSR ($\sigma'_{vy}/\sigma'_{vo}$)	S_{σ} ($\sigma'_{vy}/\sigma'_{ve}$ *)	$S_{t\ vane}$
3.15 m undisturbed	Floodplain	68 (52)	35	1.9 (1.6)	1.93 (0.92)	2
4.75 m undisturbed	Central Basin	68 (52)	50	1.4 (1.1)	11.6 (8.91)	6.5
BH825 4.2 m	Central Basin	63 (48)	37	1.7 (1.3)	30.7 (23.59)	2.6
BH825 13.2 m	Central Basin	209 (161)	90	2.3 (1.8)	4.1 (3.14)	N/A
BH832 10.2 m	Central Basin	93 (72)	57	1.6 (1.3)	(71.9)	2.21
BH809 4.2 m	Central Basin	66 (51)	41	1.6 (1.2)	13.2	24
BH809 7.2 m	Central Basin	124 (95)	58	2.1 (1.6)	20.6	20
Onsoy (Norway) 6.85 m	Central Basin	85	54	1.4	42.3	6-8

The above data illustrating the existence of sensitive clays in east coast Australian estuaries is consistent with the expectation derived from an understanding of the complex evolutionary processes in eastern Australian estuaries. The eastern Australian estuaries accommodate strikingly similar evolutionary processes to those under which all quick clay precursor material evolves. The Onsøy clay described above, the Champlain Sea clay from Canada (Leroueil *et al.*, 2003) and the estuarine clays of the Richmond River have all evolved in brackish to marine conditions. They all contain a component of shell material and organic matter concentrations in the order of 3-5%. Finally they all have evidence in the form of authigenic sulphides of anaerobic post-depositional alteration. This alteration also leaves the characteristic dark black colour relating to the presence of monosulphides. This final driver for the formation of quick clays in the case of the northern hemisphere clays is the leaching of salt from the pore fluid. With the melting of the glaciers the Canadian and Norwegian landscapes have lifted out of the ocean through isostatic rebound (Kenney, 1964). Progressively, fresh water flowing from higher in the landscape has leached salt from the marine clays thus reducing the remoulded strength and increasing the sensitivity.

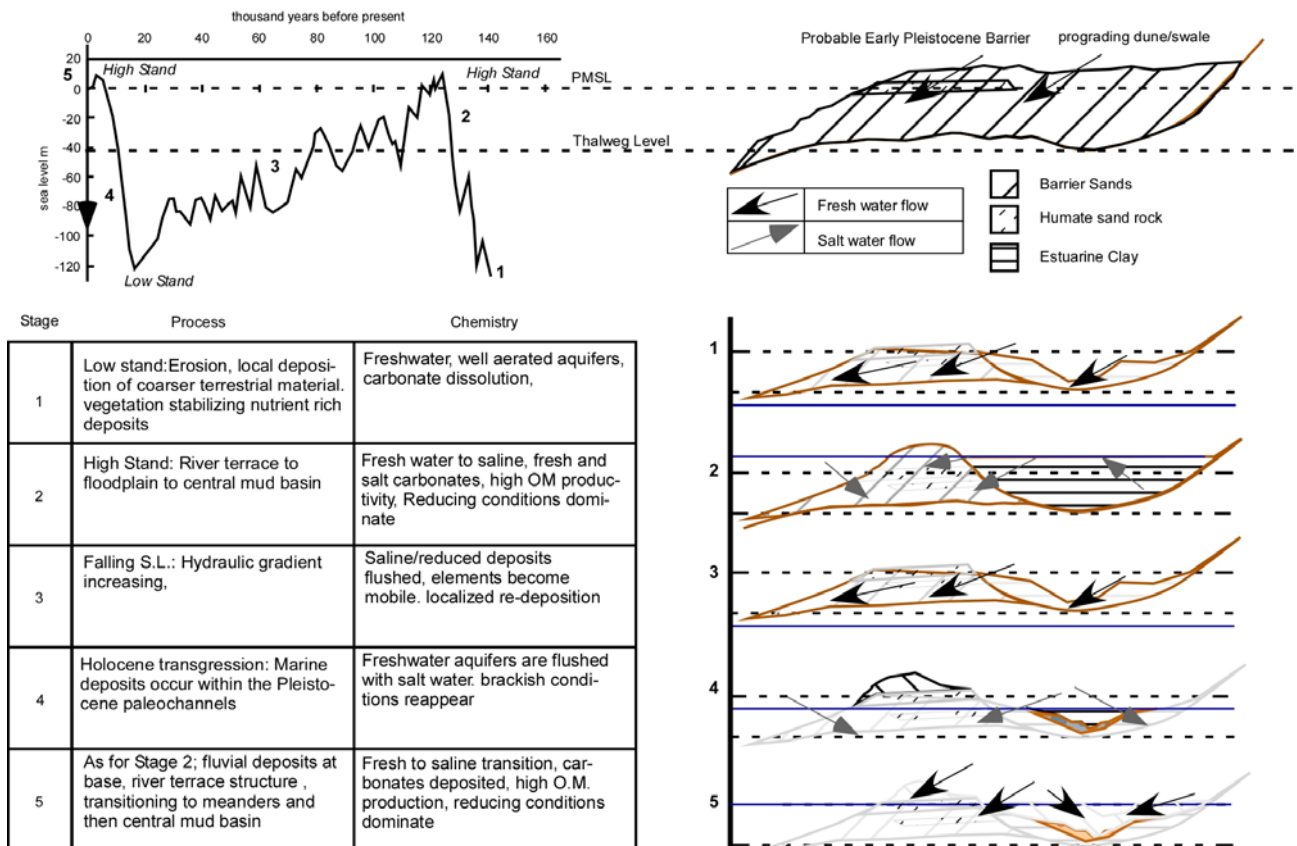


Figure 6: Mechanism for the alteration of marine clays within the Richmond River.

At first glance this last important factor may appear to be missing from the Australian situation. However Figure 6 presents the sequence of stratigraphic evolution for the Richmond Estuary relative to the regional sea level curve taken from Chappell *et al.* (1996). During two periods within the last 120,000 yrs, conditions have occurred in which fresh water gradients would exist in such a way as to flush salt water from marine deposited clays. These are at periods of relative sea level lowering. The first of these is from 120,000 yrs BP to 18,000 yrs BP. Most importantly, in the last 3000 yrs relative sea level has fallen by around 1 m. Marine clays deposited during the early Holocene transgression will have experienced a significant period of fresh water flushing. This process is being driven both by fresh water infiltration from the surface and through contact with confined fresh water aquifers that occupy previously saline tidal channel and barrier sand deposits within the clays. Initial investigations have shown that high sensitivity materials found in the Richmond River are in locations that have been exposed to fresh water flushing.

A very important difference between Australian Estuarine clays and those of the Northern Hemisphere lies in the climate and sediment supplied to the estuaries. In Australia the climate has been dominated by sub-tropical to temperate conditions and we have had no glacial periods. As a result Australian clays have evolved under intense chemical rather than physical processes and the estuarine clays (at least in the Richmond) are dominated by mixed layer clays and smectite. Since a major characteristic of extremely sensitive and quick clays is the presence of rock flour (Torrance, 1983) as the soil matrix. The rock flour is a product of mechanical abrasion by glaciers so it is unlikely that clays with this extreme sort of behaviour would occur in Australia. In terms of our future investigation into the estuarine clays of Eastern Australia and the likely development of future expensive infrastructure that may mobilise this element of the clay's behaviour it would seem necessary to reassess the way in which we look at them.

6 CONCLUSION

This paper has demonstrated presence and potential occurrence of structured clays with sensitivities ranging from low to very high in eastern Australian estuaries. A better understanding of estuary evolution allows the diverse range of complex evolutionary processes to be appreciated and the role played by them in generating structured clays. Experience with these materials in Europe and Canada gives insight into the significant phenomena associated with these clays and the possible shortcomings of CSSM for modelling the behaviour. At the same time it has been demonstrated that there are suitable differences in the composition that need to be considered when applying the northern Hemisphere experience to the Australian problem.

It is likely that many of the problems experienced in engineering infrastructure on east coast estuarine clays is related to the complex behaviours of structured clay and hence there is a need for additional research into their distribution and engineering behaviour.

7 APPENDIX

The determination of intrinsic values can also be achieved using the correlation equations proposed by Burland (1990). These correlations (Equation 2 and 3) relate the void ratio of the clay sample at the liquid limit e_L to e^*_{100} and C^*_c . The reader is referred to Burland (1990) and Chandler (2000) for the background into these derivations.

$$e^*_{100} = 0.109 + 0.679e_L - 0.089e_L^2 + 0.016e_L^3 \quad (2)$$

$$C^*_c = 0.256e_L - 0.04 \quad (3)$$

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