Application of Modern Ground Investigation Techniques to Characterise Quaternary Sediments in Kempsey, NSW

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ABSTRACT: On the Macleay River and Floodplain Bridge project in Kempsey, modern ground investigation techniques were undertaken to capture the complex soil behaviour over different geological units that were previously underestimated using conventional investigation techniques of wash boring and standard penetration tests. The ability for cone penetrometer testing (CPT) to assess strength characteristics and seismic dilatometer (sDMT) testing to capture more realistic soil characteristics and stiffness of the ground assisted in providing a more efficient and accurate design. These in-situ testing methods were correlated with laboratory testing to derive parameters whilst also considering the uncertainty depending on the quantity, quality and reliability of available data. This paper presents a comparative study of the modern and traditional ground investigation techniques and aims at challenging the conventional ground investigation approach by demonstrating the benefit these techniques can offer in potential savings and enhanced soil characterization accuracy.

1 INTRODUCTION

1.1 *Project Description*

The Macleay River Floodplain Bridge (MRFB) is a 3.2km long highway bridge across the Frogmore floodplain and the Macleay River (see Fig. 1). The bridge forms part of the overall Kempsey Bypass project which is a new 14.5km highway that bypasses the towns of Kempsey and Frederickton. The bypass forms part of the Roads and Maritime Services upgrades for the Pacific Highway.

The bridge is approximately 21.6m wide, providing two traffic lanes in each direction. The substructure is founded by concrete piles across the river and driven steel tubular piles across the floodplain.

The bridge opened to traffic in 2013 and is the longest operating road bridge in Australia. This paper covers the floodplain section only.

2 PROJECT SETTING

2.1 *Location*

The project is located near to Kempsey in northern New South Wales, Australia, approximately 55km north of the town of Port Macquarie (see Fig. 1).

2.2 *Topography and geomorphology*

The topography is generally flat as the bridge structure crosses the Frogmore floodplain and then varies as it crosses the Macleay River to Frederickton. The elevation range across the floodplain is around 1.5 to 4.75m Australian Height Datum (AHD). The height of the river banks are just over 5mAHD dropping to -3.6mAHD in the river bed.

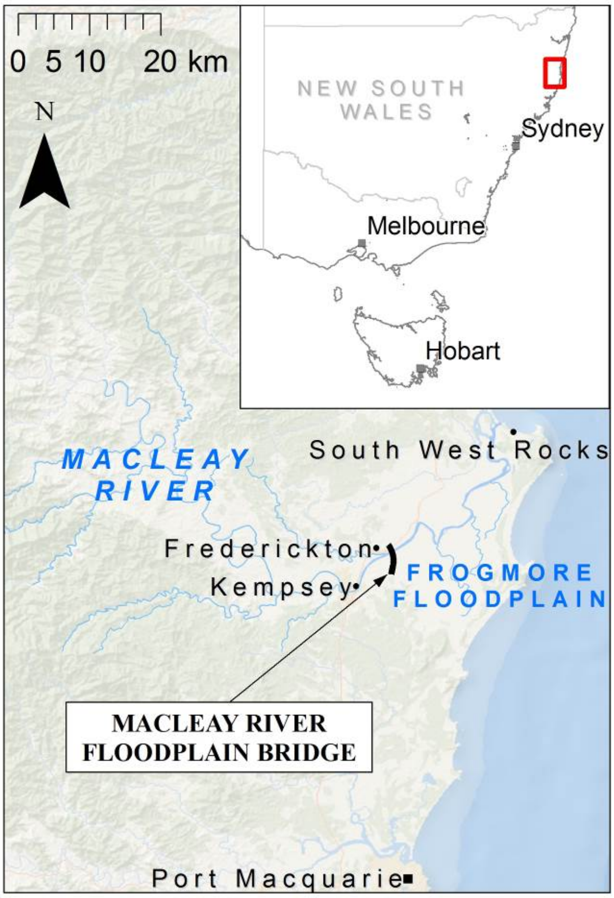

Fig. 1. Project Location

The source of the Macleay River is in the Great Dividing Range. It flows down to a wide floodplain where it follows a meandering course before entering the Pacific Ocean at South West Rocks.

2.3 *Geological History*

The geology in the area of the project comprises of bedrock overlain by Quaternary (Pleistocene and Holocene) alluvial and estuarine deposits.

The bedrock encountered was predominately siltstone of the Kempsey Beds formation. This bedrock was deposited in a marine environment in the early Permian period (Bruckner & Offenberg 1970). Since deposition the area has been subjected to intense deformation (folding) and regional metamorphism (Gilligan & Brownlow 1987) resulting in the presence of fault breccias and high angled closely spaced jointing.

When sea level started to fall around 120,000 years ago (mid Pleistocene) (Troedson et. al. 2004) the bedrock would have been intensely eroded leading to an uneven bedrock surface. Energetic rivers during this time (likely braided) scoured palaeochannels and filled the base with Pleistocene alluvial gravels. Alluvial sands and silts were then deposited in a fining upward sequence as the rivers migrated or lost energy. Sea level reached a low point around 20,000 years ago (Troedson et. al. 2004). After this sea levels rose in the late Pleistocene through to the early Holocene and estuarine deposits filled the basin. In the late Holocene either a small relative drop in sea level or the basin becoming full caused the depositional environment to change from estuarine to alluvial. Holocene alluvial sediments were then deposited in a thin mantle across the surface.

The current active Macleay River system continues to deposit or erode sediments in the river channel and on the floodplain during flood events.

3 SUMMARY OF GROUND INVESTIGATIONS

3.1 *Summary*

As part of the design of the bridge a detailed geotechnical ground investigation was undertaken on the floodplain and in the river in 2011 to supplement existing ground information. This paper discusses the data from the floodplain section only. Table 1 presents a summary of relevant testing undertaken for the floodplain investigation.

3.2 *Purpose*

The main purpose of the MRFB ground investigation was to quickly obtain high quality data that could accurately define the complex geology and enable efficient design of the bridge foundations. Other key drivers for the ground investigation were to understand the feasibility of pile driveability, quantification of lateral soil stiffness and confirmation of pile length.

Table 1. Summary of detailed ground investigation

Test type	No. tests on floodplain
Borehole by washboring with SPTs or sonic coring in superficials and rotary coring in bedrock.	167
Seismic dilatometer (sDMT)	37
Cone penetrometer testing with pore water measurement (CPTu)	10
Single stage triaxial tests with bender elements	9
Multi-stage triaxial tests	5
Oedometer tests on undisturbed and remoulded samples	8

3.3 *Investigation and testing methodology*

Boreholes were drilled through soil using rotary wash boring and sonic drilling techniques, and then cored through rock using rotary coring techniques. Sonic drilling uses high frequency resonant energy to advance the drilling rods. The continuous soil sample retrieved was logged for description and consistency of the soil which is considered to be more accurate than using wash boring techniques. This enabled direct comparisons with the sDMT data.

The DMTs were primarily scheduled to measure the constrained modulus (M) to use as a proxy for large strain modulus. Use of the seismic element also collected data to calculate the shear modulus (Go) to enable modelling of small strain stiffness. sDMTs were also specified to provide a larger dataset in order to more accurately characterise the complex geology along the alignment.

3.4 *Ground model*

Following the ground investigation the data was compiled and a geological model was developed (see Fig. 2). For the purposes of the pile design the geological long section for the bridge was divided into nine different design sections each representing an area with relatively consistent geological strata elevations.

This paper presents data from design section 1 and design section 8. Design section 1 is located at the southernmost end of the alignment in the middle of the floodplain. Design section 8 is located within the floodplain but closer to the Macleay River. These sections have been chosen as they represent distinctly different geological profiles.

4 SOIL CHARACTERISATION

4.1 *Geological units*

Six geological units were identified during the ground investigations. These units are discussed in more detail in the following sections (in order of deposition/age starting with the most recent).

4.1.1 *Holocene Alluvium*

Comprise of a wide range of sands, silts and clays which have been deposited by the current river system. Pockets of weak iron cementation and desiccation from sub aerial exposure were noted indicating a stiff crust.

4.1.2 *Holocene Estuarine*

Typically fine grained and comprises of clays and silts with some layers or lenses of clayey sands. This unit was deposited in an estuarine environment that formed as sea levels rose. It contained traces of shells and organic matter.

4.1.3 *Old Alluvium (channel deposits)*

Comprises of gravels, sands with some silt/clay generally in a fining upward sequence; indicating alluvial deposition from a meandering river system. The thickness of gravels, sub-rounding and non-local origin indicates it is likely the coarser gravels were deposited by energetic braided river systems. When the rivers lost energy the upward fining sequence was deposited. The gravels are seen to infill depressions (likely palaeochannels) in the bedrock surface.

4.1.4 *Old Alluvium (weathered)*

A distinct sub-unit only encountered towards the southernmost end of the bridge (design section 1). This comprises of a pale grey to mottled orange, high plasticity, firm to hard, fissured and cemented clay. Pockets of dark brown to black organics (including wood fragments) were found towards the base suggesting alluvial deposition. The fine grained content and organics indicate deposition in a backswamp environment. This unit has then been hardened and cemented by deep weathering and diagenetic processes.

4.1.5 *Residual soil and bedrock*

Residual soil was only encountered towards the southernmost end (design section 1) and was variable in thickness.

The bedrock encountered was predominately siltstones often with interbedded or interlaminated sandstones. Layers of highly fractured rock (closely spaced, high angle shear joints), low strength bands and fault breccias were also noted. These are likely to have resulted from the folding events that formed the syncline in the rock below the Kempsey area.

4.1.6 *Geological unit focus of this paper*

This paper focuses on the Holocene Alluvium, Holocene Estuarine and Old Alluvium (weathered) due to the limitations of obtaining sDMT data from the Old Alluvium channel deposits, residual soils and bedrock because of the high stiffness of these materials.

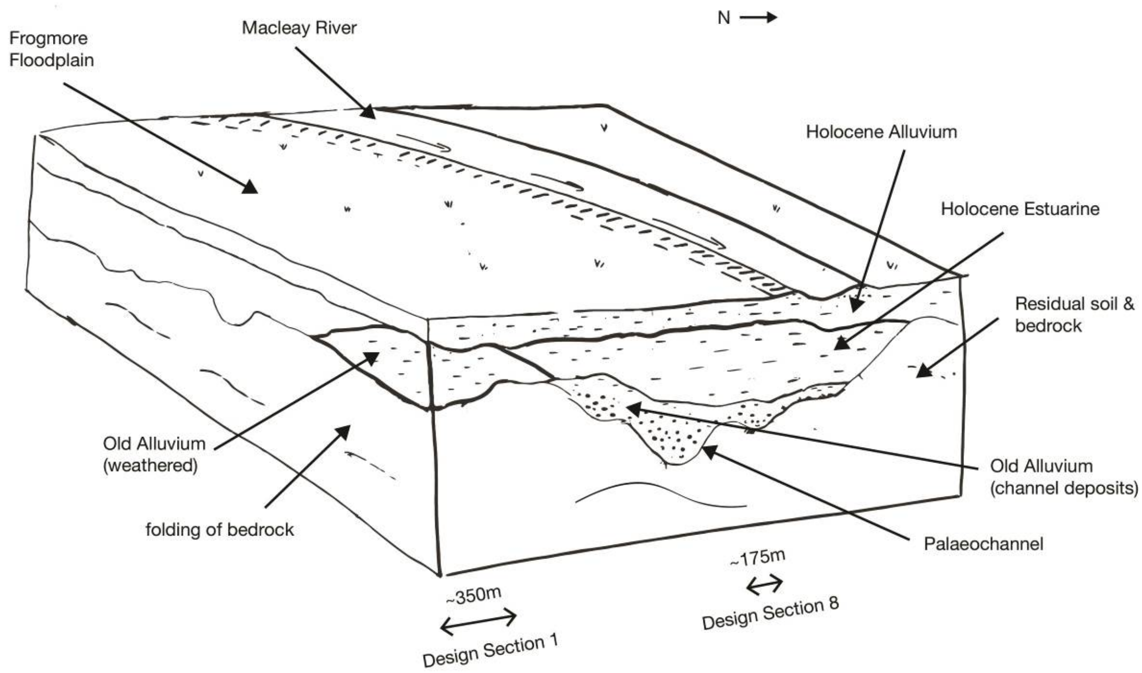

Fig. 2. 3D sketch geology

4.2 *Soil characteristics from sDMT data*

Results from the sDMTs were compared with other insitu tests, laboratory tests, borehole descriptions and published correlations in order to establish and validate the adopted design parameters. The soil characteristic parameters, Material Index (I_D) and Horizontal Stress Index (K_D) are plotted on Fig. 3 to Fig. 6 for section 1 and section 8 of the alignment and discussed in more detail in the following sections. The strata breaks in these graphs are based predominantly on the descriptions in the borehole logs from the sonic samples.

I_D determines the type of soil based on the membrane pressure reading and pre-insertion pore pressure. The soil type is identified using the following I_D ranges:

- Clay $0.1 < I_D < 0.6$
- Silt $0.6 < I_D < 1.8$
- Sand $1.8 < I_D < (10)$

K_D is derived using the membrane pressure readings and existing overburden pressure and gives an indication of over consolidation ratio. K_D for normally consolidated clay is approximately 2.

4.2.1 *Section 1*

The borehole logs within section 1 indicate 0.8m to 4.3m Holocene Alluvium over 14.4m to 27m Old Alluvium (weathered) with a thin residual soil profile over bedrock.

Fig. 3 indicates the material consistently behaves as clay to silty clay for the Holocene Alluvium and Old Alluvium (weathered) which correlates well with the borehole logs.

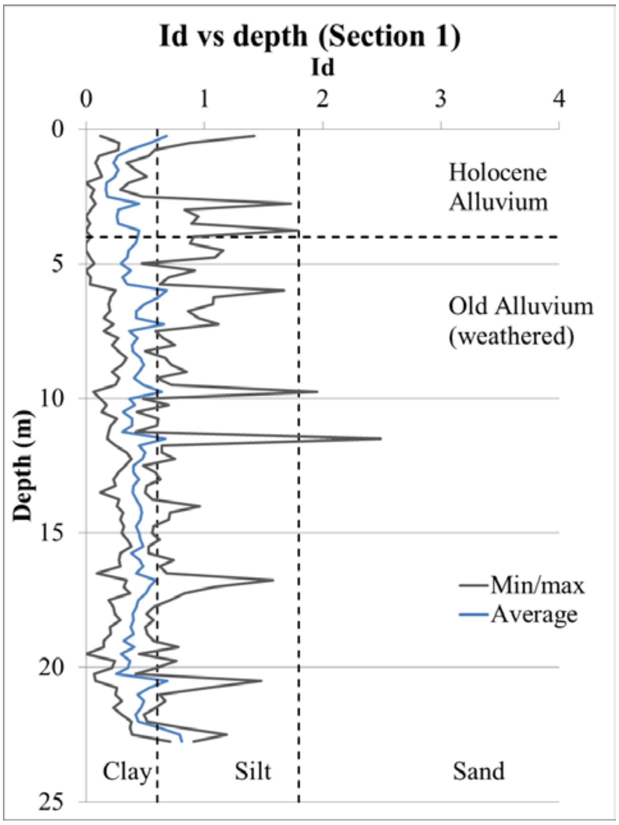

Fig. 3. Material Index, I_D (Section 1).

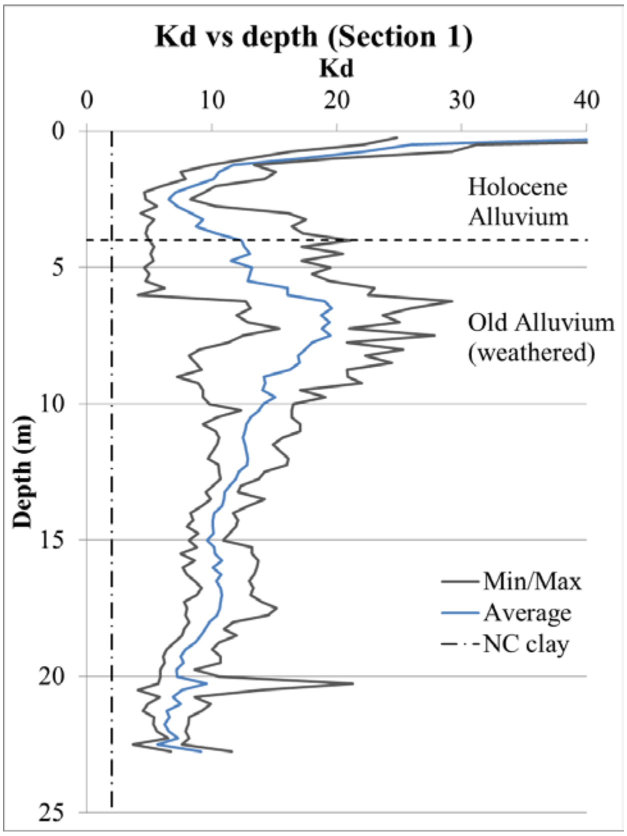

Fig. 4. Horizontal stress index, KD (Section 1).

Fig. 4 indicates that the upper section of the Holocene Alluvium and the Old Alluvium (weathered) is overconsolidated. The geological history does not indicate this is due to a reduction in overburden therefore this apparent overconsolidation is likely to be a result of cementation or structure in the soil. This correlates well with the observation of iron cementation noted in the borehole logs. Cementation and soil structural alteration are common in areas of Australia where there is a generally warm climate and repetition of desiccation (dry seasons) and rewetting (wet seasons or flood events).

4.2.2 *Section 8*

The borehole logs indicate 3.6m to 5.3m Holocene Alluvium overlying 21.5m to 29.4m Holocene Estuarine overlying coarse grained Old Alluvium (channel deposits) overlying weathered bedrock.

Fig. 5 indicates that the material is variable and is likely to be interbedded layers from silty clay through to sand in a fining upwards sequence which correlates well with the borehole logs. The I_D results tend to slightly overestimate the fines content as the borehole logs typically indicate coarsening from sandy silt to silty sand at 16m depth. Clay is also generally not present below 5m depth in the logs. However, as this is a material behaviour index the results from the DMT are still meaningful for characterising the ground conditions.

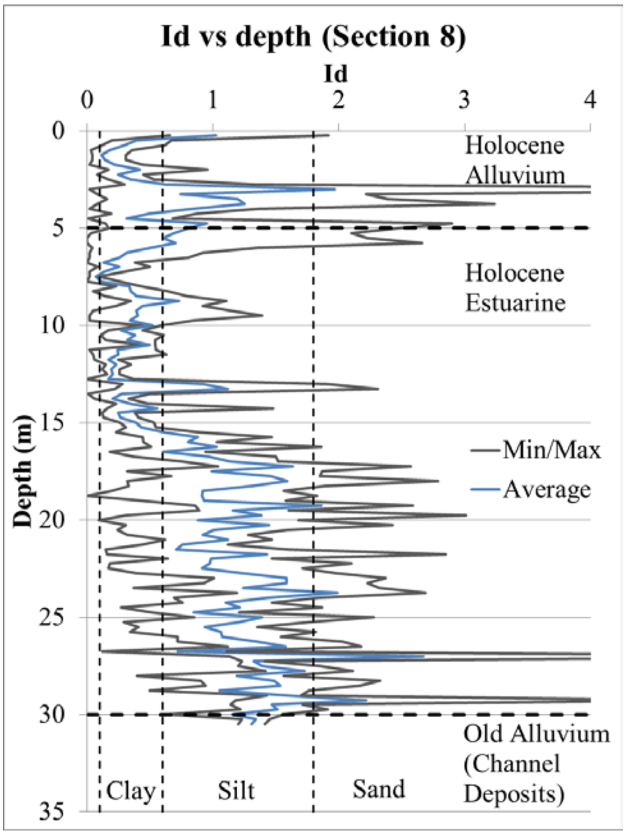

Fig 5. Material Index, I_D (Section 8).

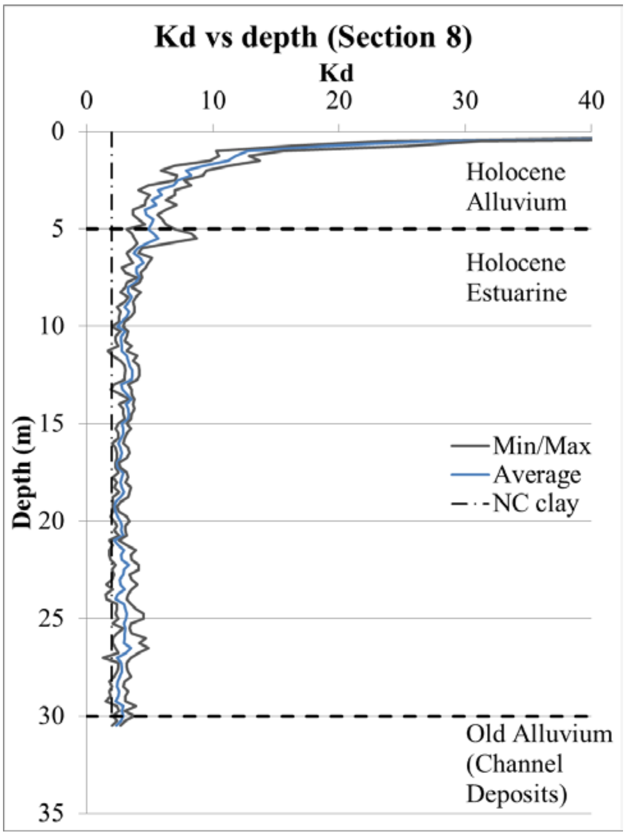

Fig. 6. Horizontal stress index, K_D (Section 8).

Fig. 6 also indicates a high overconsolidation ratio (OCR) towards the surface in the Holocene Alluvium (cemented or structured crust) which reduces with depth. The Holocene Estuarine is slightly overconsolidated which is also unexpected of this kind of material due to the deposition environment.

5 STIFFNESS

5.1 *Derivation of stiffness parameters*

The shear modulus (Go) and constrained modulus (M) derived from the sDMT/DMT respectively were compared to similar parameters derived from published correlations for CPTs, SPTs, triaxial and oedometer tests. The derivation and results for section 1 and section 8 are presented in Fig. 7 and Fig. 8 and discussed in more detail within this section. The various constrained moduli (M) were calculated using the Eq. (1) to Eq. (5) below.

$$M_{DMT} = R_M \times E_D \text{ (ISSMGE 2001)} \quad (1)$$

$$M_{CPT} = 4q_t \text{ (Lunne et. al. 1997)} \quad (2)$$

$$M_{OED,NC} = \frac{\left(\left(1+e_o\right)*\sigma'\right)}{0.435*C_c} \text{ (Lambe \& Whitman 1979)} \quad (3)$$

$$M_{OED,OC} = \frac{\left(\left(1+e_o\right)*\sigma'\right)}{0.435*C_s} \text{ (Lambe \& Whitman 1979)} \quad (4)$$

$$M_{TRI} = \frac{\sum\sigma}{\sum\varepsilon} \quad (5)$$

The maximum shear modulus was calculated using the seismic shear wave velocity using Eq. (6).

$$Go = pVs^2 \text{ (Lunne et. al. 1997)} \quad (6)$$

As shown in the below figures the sDMT/DMT indicate a much greater in-situ stiffness than the stiffness derived from SPTs. However, the stiffness is only slightly greater than that derived from CPTs for normally consolidated material (as indicated in design Section 8, Fig. 7) and significantly greater than that derived from CPTs for overconsolidated material (as indicated in design Section 1, Fig. 8). This was important during detailed design as due to the structural arrangement a higher stiffness attracted higher bending moments at the upper section of the piles. Adopting a lower stiffness may have led to underestimating the bending moments generated in the piles.

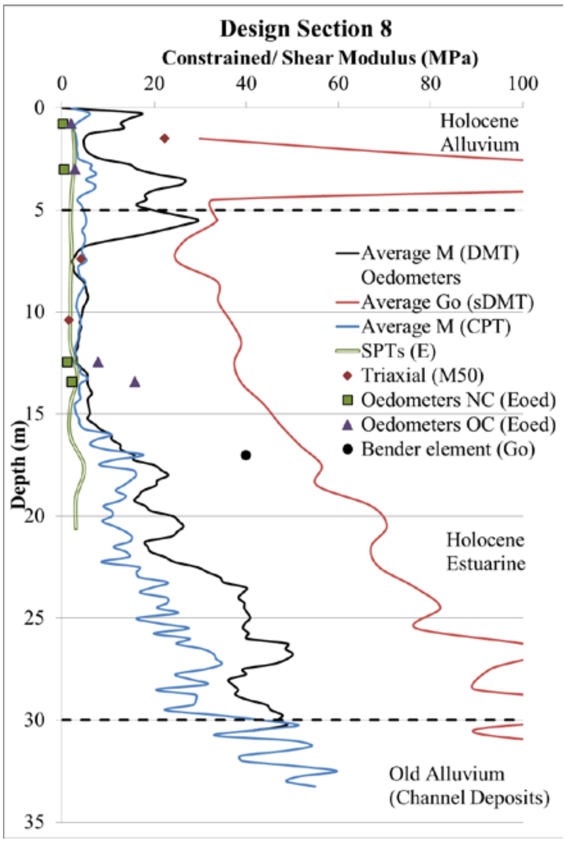

Fig. 7. Comparison of constrained and shear modulus from different testing methods (Section 8).

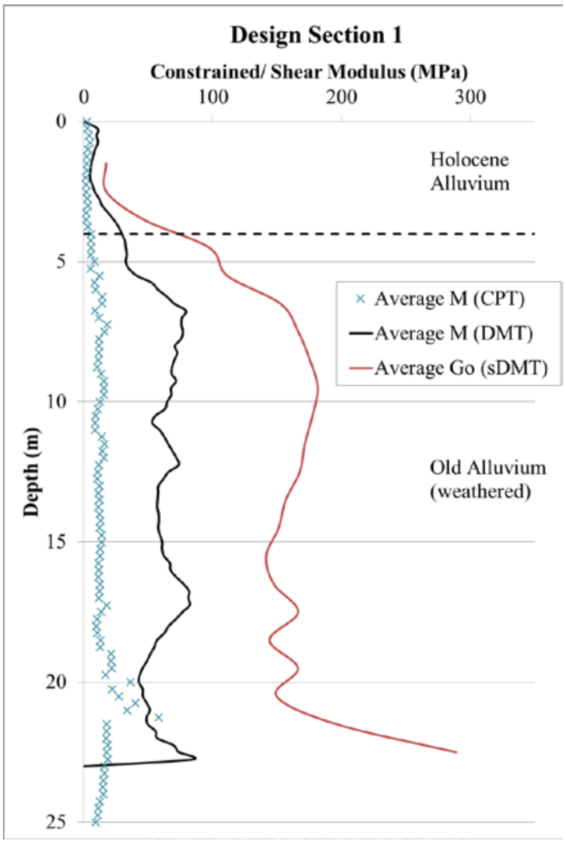

Fig. 8. Comparison of Constrained and shear modulus from different testing methods (Section 1).

5.2 *Comparison of geological unit stiffness*

5.2.1 *Holocene Alluvium*

The borehole logs and oedometer testing suggested that the Holocene Alluvium is predominantly soft in consistency with firm lenses. The triaxial and DMT test results however indicated a stiffer ‘crust’ material (see Fig. 7). It should be noted that the oedometer results in this area exhibited signs of sample disturbance (as it is difficult to obtain an undisturbed sample in a variable material). The stiffer crust was only identified from the DMT and continuous sampling from the sonic cores which enabled this unit to be investigated further. This included additional oedometer tests on soaked remoulded samples to demonstrate that the material would not soften during a flood event.

5.2.2 *Holocene Estuarine*

The borehole descriptions and SPT modulus derived in Fig. 7 suggested the Holocene Estuarine to be very soft/soft with SPT ‘N’ values of 0 typically reported. The oedometer test results ranged significantly depending on whether the soil was assumed as normally consolidated or overconsolidated. Even though the oedometer results were of poor quality, the stiffness derived from the overconsolidated soil was comparable to that derived from the DMT. The CPT and DMT results typically suggested a firmer material than the other tests. It is also important to note that the stiffness derived from the triaxial tests was lower than the other tests types in this unit.

The maximum shear modulus from the sDMT correlated reasonably well with the shear modulus measured from the triaxial bender elements test.

5.2.3 *Old Alluvium (weathered)*

Old Alluvium (weathered) is typically logged in boreholes as firm to hard in stiffness. Fig. 8 indicates a large discrepancy between the constrained modulus derived from the CPT (and SPTs) and that from the DMT.

The deep weathering profile has resulted in a high apparent OCR in which the material behaviour changes upon shearing. The lower level of disturbance from the DMT compared to the CPT reduced the amount of shear deformation in the soil, subsequently producing much higher and more realistic moduli results.

5.3 *Comparison of Overconsolidation ratio and constrained modulus*

As discussed in Section 5.2, the greatest difference in M between DMT and CPT was encountered in Old Alluvium (weathered), which was potentially due to the high apparent OCR and soil structure. The importance of stress history in determining modulus was identified as early as 1988 (Jamiolkowsi et. al.) and further discussed in other papers. OCR from the DMT data has been calculated using Eq. (7).

$$OCR = \left(0.5 * K_D\right)^{1.56} \quad \text{(ISSMGE 2001)} \tag{7}$$

Fig. 9 compares M_{DMT} and M_{CPT} against OCR. The Old Alluvium (weathered) unit in section 1 was the only unit which showed a trend with the M_{DMT}/M_{CPT} modulus ratio against OCR. Whilst the data suggests that OCR is potentially a factor explaining variation in reported moduli between the two test methods, this indicates there are other factors such as weathering and cementation that might play an even bigger role.

Go/M_{DMT} was also plotted against OCR in Fig. 10 to ascertain if a constant could be used to relate the constrained modulus to the maximum shear modulus. The Old Alluvium (weathered) and Holocene Alluvium (section 1) units show use of a constant maybe be suitable but the Holocene Estuarine and Holocene Alluvium (section 8) results both indicate this would be lower bound. Similar to that reported in Monaco et. al. (2009), it appears that the lower the OCR and the coarser the grain size, the more inconsistent the Go/M_{DMT} ratio is. Without the sDMT, calculation of the shear modulus of the material would have been underestimated especially in the layers with low OCR.

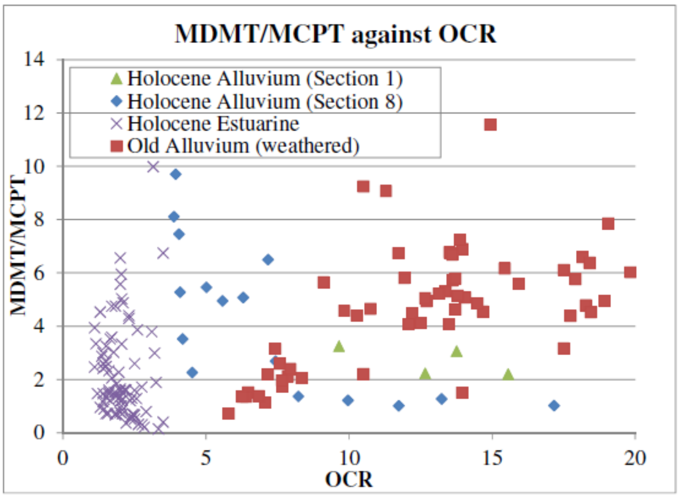

Fig. 9. Comparison of OCR against M_{DMT}/M_{CPT}.

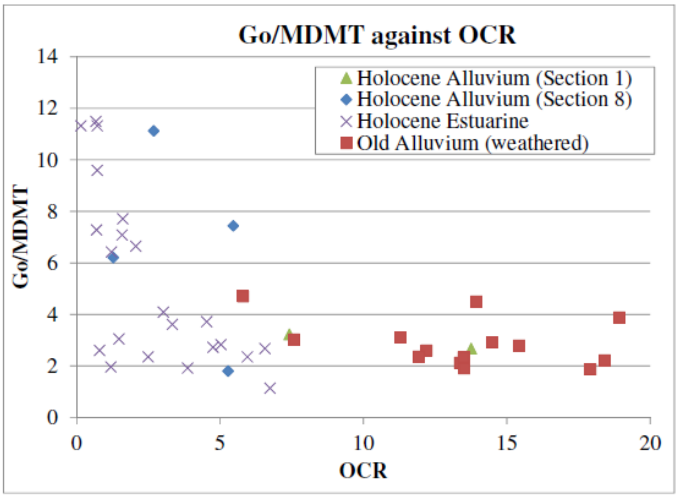

Fig. 10. Comparison of OCR against Go/M_{DMT}.

6 STRENGTH

The laboratory test results generally indicated that all the geological units were low in stiffness but high in strength which is unexpected for these types of materials. The strength measured from the triaxial test results were compared with results derived directly from the DMT results. Using the Eq, (8) from ISSMGE (2001).

$$\phi = 28° + 14.6° * \log(K_D) - 2.1° \log^2 K_D \qquad (8)$$

Note that the friction angle formula above is only provided where the I_D value is larger than 1.8 (indicative of sandy silts or coarser). As undisturbed samples are generally taken in fine grained material, there were only two triaxial tests that enabled direct comparison with the DMT. Both samples from triaxial and DMT were closely matched and indicated a high friction angle (approximately 38°).

Having the ability to provide more accurate in-situ strength parameters for coarse grained material is valuable as historically strength is mainly based on engineering judgement and limited correlations with in-situ tests.

7 CONCLUSION

The sDMT proved invaluable for MRFB in three key areas: magnitude of dataset, consistency of results and accurate representation of in-situ soil behaviour.

The sDMT proved to more accurately determine the ground conditions and provided a more representative characterisation of the geology (with a larger data set) along the 3.2 km long bridge when compared with standard ground investigation techniques employed in Australia. The more accurate assessment of material strength and stiffness parameters of the floodplain geological units resulted in a more precise ground model. This ground model then enabled accurate and efficient foundation design which resulted in significant cost and programme savings for the project. Additionally, when compared directly per metre length the sDMTs were fifty percent cheaper and two to three times more productive than washboring.

It is suggested that when correlated against boreholes and CPTs, the seismic dilatometer can provide enough detailed information to be used as a primary investigation technique in soils. They can also offer cost and programme savings if some boreholes are substituted with sDMTs. This suggestion is a viable way to minimise capital expenditure on large infrastructure projects whilst still retaining sufficient information to enable design.

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