Characterisation of Carse Clays using Seismic DMT

Anthony O'Brien[1#] and *Ian* Murray[1]

[1]*GE Solutions Consulting Ltd, Unit 1 Burnhouse Industrial Estate, Whitburn, West Lothian EH47 0LQ*
[#]*Corresponding author: info@ge-solutions.co.uk*

ABSTRACT

The estuarine sediments around the head of the Forth estuary deposited during and after the Flandrian interglacial are an important, economically productive regional soil horizon in Scotland. The soil has been extensively studied locally (Hight et al., 1992) at the Bothkennar EPSRC site however, to the authors' knowledge seismic dilatometer testing using Marchetti's Medusa apparatus has never been used to characterise the material. Taking data from a number of sites and using an automated Medusa seismic dilatometer apparatus, a complementary contribution to the characterisation of the site which includes some comments on spatial variability of the material and other observations are presented.

Keywords: Marchetti dilatometer; Seismic dilatometer; Geophysics; Carse Clay;

1. Background geological environment and economic setting

The expansive plain of post-glacial deposits in the estuaries of the River Forth and River Tay in Scotland are known colloquially as the Carse Clays. These are young sediments of the Flandrian transgression of the Quarternary period in the Midland Valley of Scotland and broadly comprise marine & estuarine sediments, river alluvium, peat and (rarely) blown sands (Francis et al.,1970). Within the spatial purview of the River Forth, there are numerous Carse subsets such as the *Carse of Stirling* and the *Grangemouth Silt* members (BGS, 2023)

The colloqialism *carse* is derived from the old Scots gaelic *córrsa* meaning *course*. *Kerse* is a typical anglicised placename associated with such an area. Associated with river complexes, the Carse Clays underlie historically important economic regions in Scotland such as Perthshire, Stirling and Grangemouth.

Grangemouth, in particular, is an important port and centre of industry & energy production, now in a challenging phase of transition from petrochemical refinement to renewable energies and salient ground conditions will be important considerations in both new construction and decommissioning of old structures as well as being an apposite consideration to substantial climate adaptation infrastructure, such as flood defences.

Stirling, as a contrasting example, is a bustling university city & tourism hub with an expanding population and ambitious local council (Stirling Council, 2023) with a wide geographical purview encompassing many prosperous towns such as Aberfoyle, Cambusbarron, Fallin and Throsk. The land development associated with the population expansion has recently given rise to problems of settlement and foundation instability (Scottish Housing News, 2022; Scottish Nationalist Party, 2022) as more marginal and periphery land is developed encroaching onto deeper Carse Clay deposits.

1.1. Sites

The present study is the first in what is hoped to be an ongoing extensive examination of advanced in situ investigations in the Carse Clay complexes. The authors have long held the belief that, in broad terms, intrusive drilling operations should be de-prioritised in the UK for geotechnical characterisation and used more for geological characterisation and logging. Sparse geotechnical drilling coupled with high-intensity advanced in situ characterisation, such as cone penetration testing (CPT), self-boring pressuremeter testing, dilatometer testing (DMT) and geophysics is preferrable both commercially and in terms of the quantum of data produced. Direct-push methods are particularly expeditious, in this sense making CPT and DMT commercially attractive.

Three sites were studied in Grangemouth (2nr) and Throsk (1nr). It is hoped that the in situ testing will be sufficient to characterise the Carse Clays effectively while also demonstrating the regional spatial variability inside of a common geological setting.

2. Seismic Marchetti Dilatometer (SDMT, Medusa)

The Marchetti Dilatometer has been used since the early 1980s as an advanced in situ test. Recent improvements to the methods of operation have improved repeatability and reliability. The current automated iteration of the device, the Medusa – see Figure 1 - uses a computer-controlled actuator with hydraulic oil instead of compressed gas to inflate the membrane, effectively removing the potential for operator error. In addition, a seismic module can be added to the Medusa such that the DMT and seismic measurements are taken in the same push.

The apparatus facilitates downhole seismic shear and compression wave measurements from a surface source of excitation. In the studies presented here, only S-wave measurements are made as the P-wave measurement module was not available at the time. Seismic measurements were taken exclusively with the Medusa, not with a CPT-mounted module which will be the subject of future study and comparison.

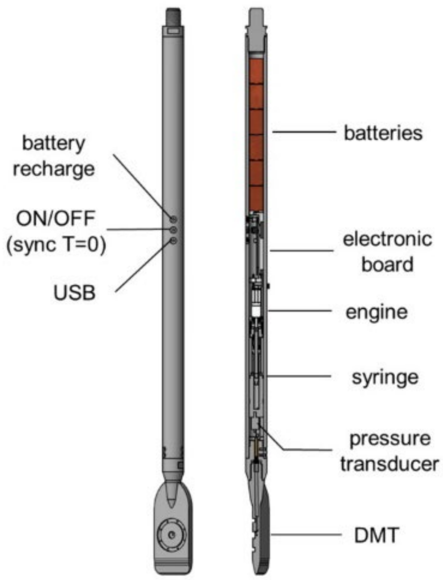

Figure 1. Medusa DMT extracted from https://www.marchetti-dmt.it/instruments/medusa/

2.1. Complementary cone penetration tests

Recent work, most notably Monaco (2022), has shown that combined use of CPT and DMT can be a powerful means of site characterisation by reducing the reliance on a single source technique and using inter-relationships to improve reliability. The potential of combined seismic testing (typically down-hole measurements of shear wave velocity) with advanced in situ testing has also been demonstrated by researchers – see for example Amoroso et al. (2014).

To this end, each dilatometer used in this study has been complemented by two adjacent cone penetration tests. The cone penetration testing was undertaken using 15cm^2 subtraction cones with the pore filter in the u2 position and pushed hydraulically in accordance with ISO 22476-1:2012.

The tip resistance, sleeve friction and dynamic porewater pressures are presented in Figures 2 to 4 respectively for the various sites.

It should be noted that there are depositional discontinuities (varying raise and fall of sea-level) at the Grangemouth sites that, despite their proximity to the EPSRC site, distinguish these sites in the upper 10m. It should also be noted that the advanced in situ testing presented by Hight et al. (1992) limited the investigations to the upper 20m. It should be further noted that the Grangemouth sites are subject to an upper and lower groundwater table, the uppermost being in direct hydraulic connectivity with the Forth and thus subject to substantial tidal range. The carse clay at the Throsk site is notably shallower as was expected from the geological memoirs, generally limited to the upper 8m at the site investigated and with a greater prevalence of distinct peat layers. Groundwater level is nominally static at this site.

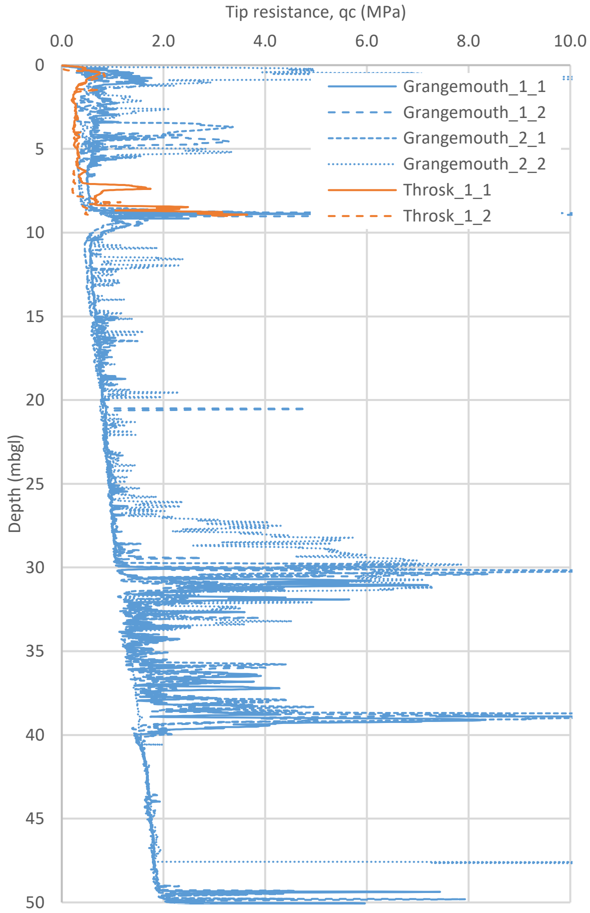

Figure 2. Tip resistances for the various sites

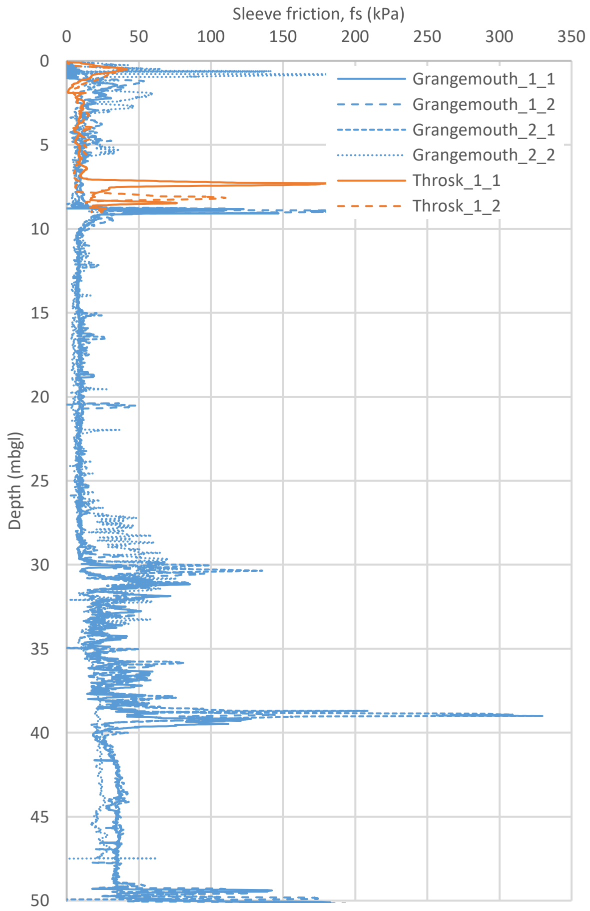

Figure 3. Sleeve friction results for the various sites

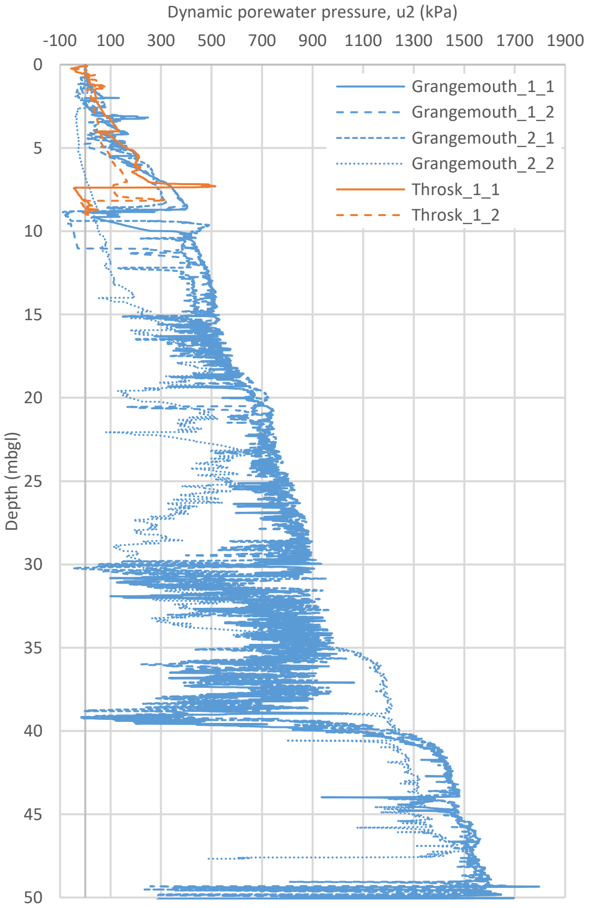

Figure 4. Dynamic porewater pressure results for the various sites

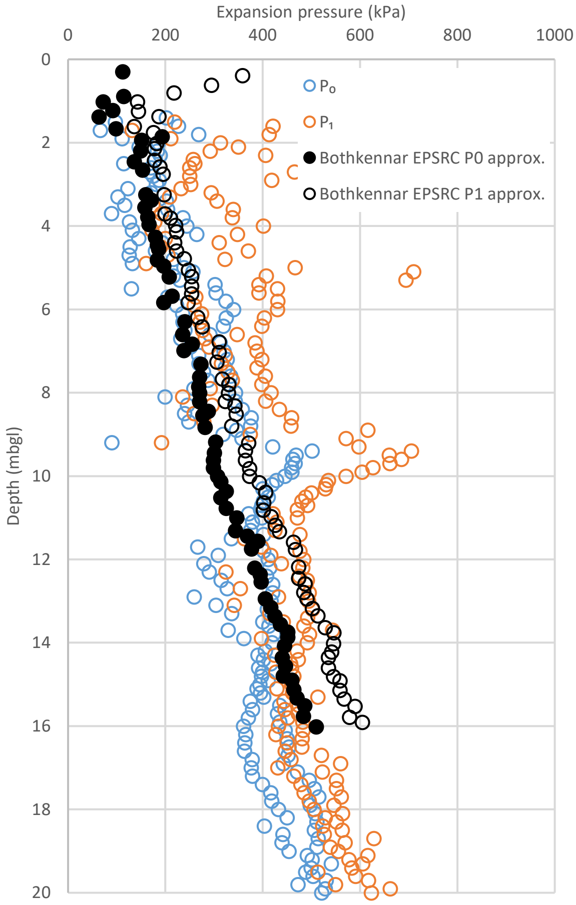

Figure 5. DMT expansion pressures combined for Grangemouth sites

3. Fieldwork results

DMT expansion pressures are presented in Figures 5 & 6 for the Grangemouth (combined) and Throsk sites respectively. In order to provide a comparison to the EPSRC site, a plot digitiser was used to infer the data from the Hight et al. (1992) paper to allow plotting on these charts. This should be considered an approximation of this data. The upper 20m of the data represent the Grangemouth Silts with materials below this comprising other formations of glacial / post-glacial origins. The Carse Clay is limited to a veneer of 8m (inclusive of a desiccated crust) at the Throsk site and is formally the Carse Of Stirling. The general progression of linear increase with depth is apparent here.

In particular, the Throsk site shows very good agreement with the ESPRC data with very similar P_0 and P_1 measurements. The Grangemouth sites, in contrast, are characterised by much more variability in the measurements in the upper 10m and generally more higher measurements of P_1-P_0 essentially implying a higher dilatometer modulus when compared to the ESPRC data. Below 10m, expansion pressures are lower.

The associated seismic velocity measurements derived from the S-wave measurements are presented in Figure 7 for both sites. Seismic measurements were made using true interval geophones at 0.5m depth increments. The signals were passed through a 4^{th} order Butterworth filter at a cut frequency of 180Hz. The coefficient of variability for these signals did not exceed 5% below 2m depth, typically less than 2%.

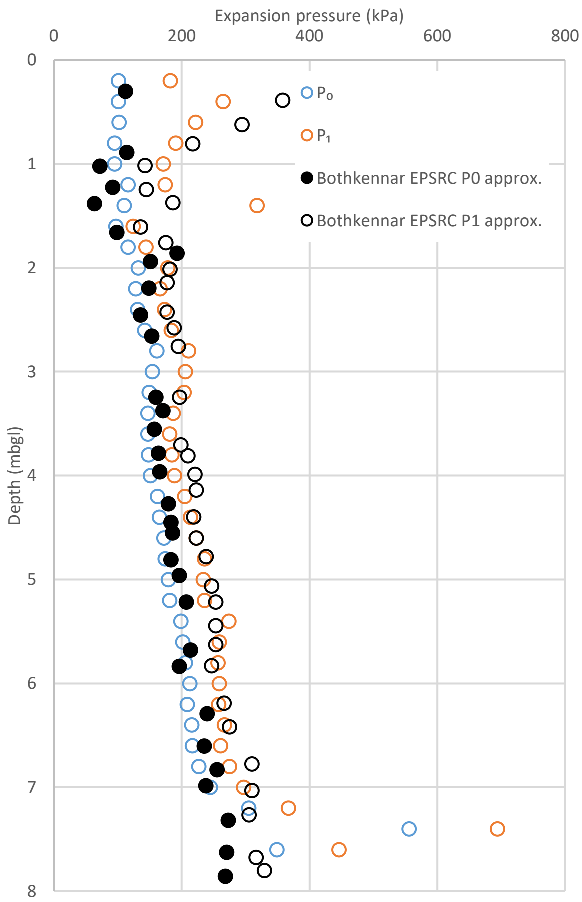

Figure 6. DMT expansion pressures for Throsk site

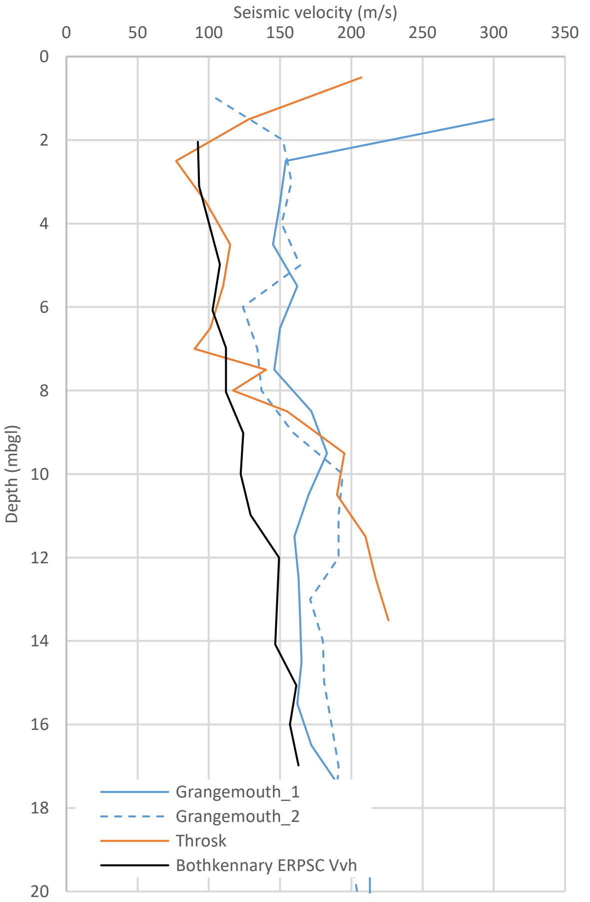

Figure 7. Seismic velocity measurements

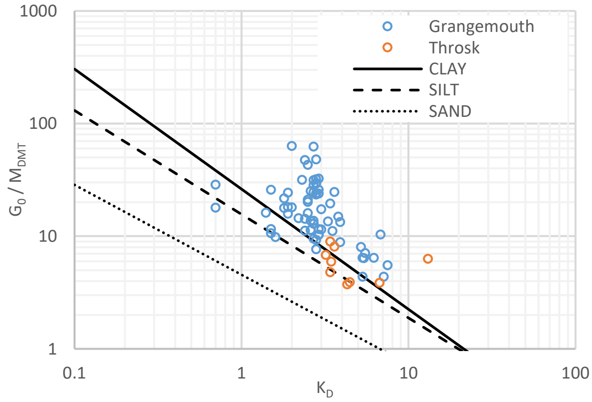

Figure 8. Ratio of G_0/M_{DMT} versus K_D for Grangemouth and Throsk sites

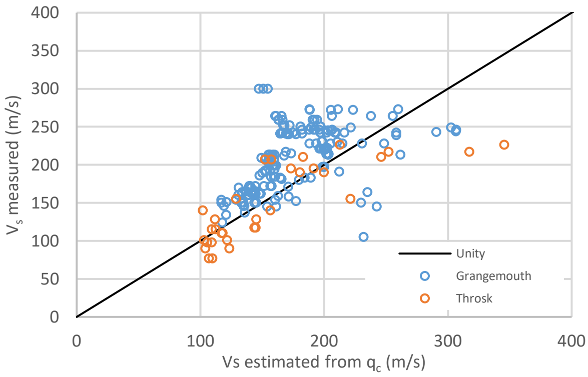

Figure 9. Measured versus estimated shear wave velocity based on CPT correlations

4. Characterisation

The interrelationship between small-strain shear modulus (G_0) and operative modulus (M_{DMT}) has been explored previously (Marchetti et al., 2008; Monaco et al., 2009) indicating that the ratio of G_0 / M_{DMT} and horizontal stress index, K_D, can be correlated with basic soil behaviour type (clay, silt, sand). Figure 8 below shows the relationships proposed by Monaco et al., 2009 with the data from the present study overlaid. Collectively the data concur with the proposed lines insofar as material behaviour broadly defines clays or silts however, it is noteworthy that some of the Grangemouth data falls outside of the ranges observed by Monaco et al. (2014) where G_0/M_{DMT} was generally observed to be in the range 8-20. A more complex depositional environment, fabric and microstructure may explain this, also noting the broader range of K_D. The data corroborate the observation of Monaco et al. that G_0/M_{DMT} is not constant even in similar constitutive materials. Shear wave velocity (V_s) measurements correlated well with CPT for both sites using the relationship proposed by Mayne & Rix (1995) which is shown in Figure 9 below, noting that the correlation would typically under-predict V_s at less than 200m/s and over-predict V_s above this. The direct V_s measurements were found to correlate well with normalised K_D measurements (Figures 10 & 11) noting, tentatively because there is substantially less data available from the Throsk site, that there is spatial variation in the relationship despite the material being constitutively similar.

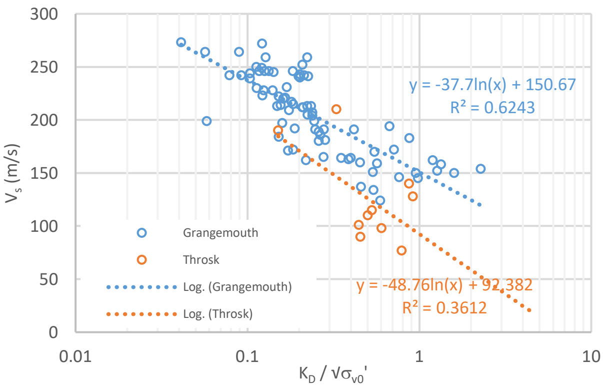

Figure 10. Measured shear wave velocity versus normalised K_D from DMT

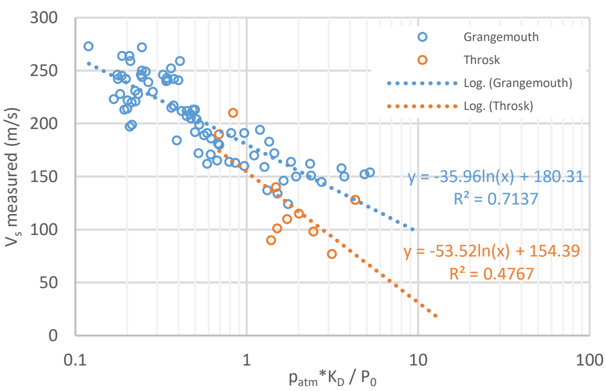

Figure 11. Measured shear wave velocity versus normalised K_D from DMT

5. Conclusions

The data collected and presented in this study demonstrates the potential of DMT as a characterisation tool in a particular geological setting, especially when paired with seismic measurements. Measurements of shear wave velocity, extracted via filtered true-interval S-wave measurements, have been found to be reliably correlated with the horizontal stress index (K_D) when normalised with vertical effective stress or initial expansion pressure. It has also been demonstrated that measured G_0 and M_{DMT} ratios are purposeful in establishing basic soil behaviour types even over a wide range of K_D. However, of most value is the facility of these advanced measurements to quantitatively demonstrate the spatial variance of what are very similar soil types and to pick up stratigraphical complexity.

It is hoped that further site investigations can be added in time to examine further sub-units of the Carse Clays along the Forth estuary. Furthermore, it is hoped this study will form the start of a broader examination into advanced in situ test characterisation of Carse Clay as a regionally important soil horizon and progress the idea that a high volume of high-quality in situ testing can be used to develop geotechnical frameworks that sit inside of regional geological contexts that adequately provide geotechnical information for advanced analytical methods such as material point methods, particle mechanics and cavity expansion theory which are more amenable to advanced in situ testing back-analysis than more traditional / rudimentary soil modelling frameworks while also facilitating statistical assessment of spatial variability and distribution on a regional basis as well as on a site-specific basis.

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