High pressure dilatometer testing in Dublin Boulder Clay

Essais au dilatomètre haute pression dans l'argile morraine de Dublin

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ABSTRACT

Geotechnical engineering in Dublin is dominated by work in the Dublin Boulder Clay (DBC) which is a lodgement till formed beneath the ice sheet that covered much of Ireland during the last glaciation. The material is very competent from an engineering viewpoint being strong and stiff with low permeability. However the material is not easy to investigate due to the high content of coarse particles. Cone penetration testing (CPT) is not possible except to very shallow depths and standard penetration tests (SPT) often "refuse" in the dense material or on the coarse particles. In an attempt to provide detailed design parameters for the Dublin MetroLink project some high pressure dilatometer (HPD) tests were performed in the material. The methods used and problems encountered are described. The angle of shearing resistance (ϕ') and the shear stiffness values derived are relatively consistent with those obtained from other methods. The values of the coefficient of horizonal effective stress (K_0) are somewhat greater than those conventionally used in design.

RESUME

L'ingénierie géotechnique à Dublin est dominée par les travaux sur l'argile morraine de Dublin (DBC), un till de dépôt formé sous la calotte glaciaire qui recouvrait une grande partie de l'Irlande lors de la dernière glaciation. Ce matériau est très performant d'un point de vue technique, car il est résistant, rigide et peu perméable. Cependant, son étude est complexe en raison de sa forte teneur en particules grossières. Les essais de pénétration au cône (CPT) ne sont possibles qu'à très faible profondeur, et les essais de pénétration standard (SPT) échouent souvent dans le matériau dense ou sur les particules grossières. Afin de fournir des paramètres de conception détaillés pour le projet Dublin MetroLink, des essais au dilatomètre haute pression (HPD) ont été réalisés sur ce matériau. Les méthodes utilisées et les problèmes rencontrés sont décrits. L'angle de résistance au cisaillement (ϕ') et les valeurs de rigidité au cisaillement obtenues sont relativement cohérentes avec celles obtenues par d'autres méthodes. Les valeurs du coefficient de contrainte effective horizontale (K_0) sont légèrement supérieures à celles traditionnellement utilisées en conception.

Keywords: HPD; lodgement till; angle of shearing resistance; in situ stress; shear stiffness.

1. Introduction

Bedrock in the Dublin area is a thin to medium interbedded homogenous grey argillaceous limestone and calcareous shale. Over much of the city, it is overlain by glacial deposits, known colloquially as Dublin Boulder Clay (DBC). This is hard lodgement till which was deposited beneath the ice sheet that covered much of Ireland during the Pleistocene period. The grinding action of this ice sheet, as it eroded the underlying rocks coupled with its loading effect, resulted in the formation of a very dense / hard, low permeability deposit, which contains pockets or lenses of coarse gravel (Farrell and Wall 1990). An exposure of the material from a site in Central Dublin is shown in Figure 1.

The material has been relatively well researched (Long and Menkiti 2007a, 2007b; Long et al. 2025) and is characterised by its high density, shear strength and stiffness and its low water content, plasticity and permeability.

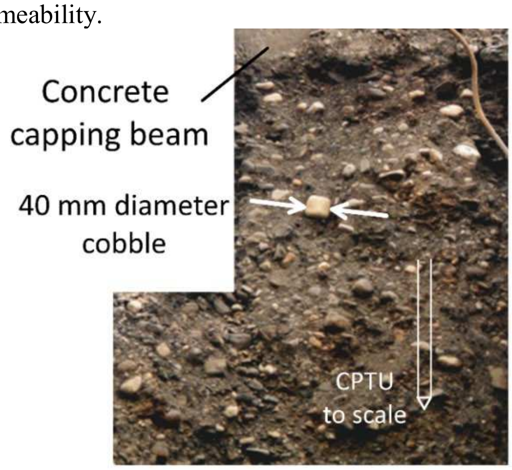

Figure 1. Exposure of the Upper Black Dublin Boulder Clay (UBkBC) at Clarendon St., Central Dublin. Dimensions of a SPT or CPT tool are shown (Long et al. 2025).

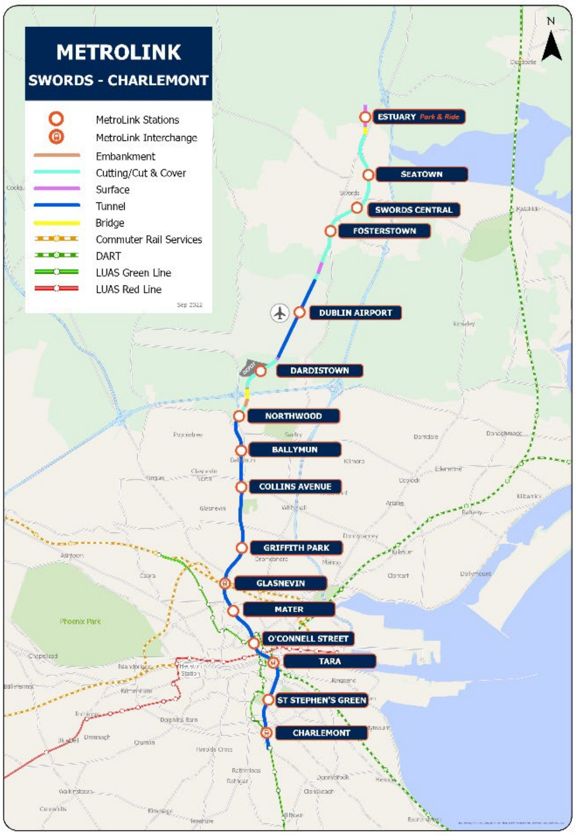

Figure 2. Route of Dublin MetroLink (https://www.metrolink.ie)

A particular characteristic of the material is its relatively high content of coarse particles. This high coarse particle content limits in situ testing such as cone penetration testing (CPT) to very shallow depths and refusals are frequently encountered during standard penetration testing (SPT).

During a recent ground investigation for the proposed MetroLink project which will connect Dublin City Centre to Dublin airport in tunnels, some high-pressure dilatometer tests (HPD) were trialed to attempt to overcome the difficulties with the other in situ techniques.

This paper will describe the techniques used as well as practical issues associated with the HPD testing. The main aim of the work was to provide design input of key properties such as the coefficient of horizontal effective stress (K_0), the effective angle of shearing resistance and the variation in shear stiffness with strain.

2. Site location

MetroLink is a proposed 18.8 km light rail scheme, mostly in tunnel, connecting the city centre with Swords in north County Dublin via Dublin Airport. The proposed route is shown in Figure 2. Extensive ground investigations, including HPD testing were carried out by Causeway Geotech in 2019 (NBH series). HPD testing was sub-let to In Situ Site Investigation.

Data reported here is taken from eight locations along the entire route, mostly at the proposed station sites.

3. Details of soils studied

3.1. Index properties

Here data from testing of the Dublin Boulder Clay (DBC) is presented only. Other tests were carried out on fluvio-glacial gravels and weathered bedrock, but these are not included. The index test data reported on Figure 3 is from samples at the same depths and locations as the HPD tests. Sampling was by means of Geobore S wireline triple tube coring so sample quality is very good.

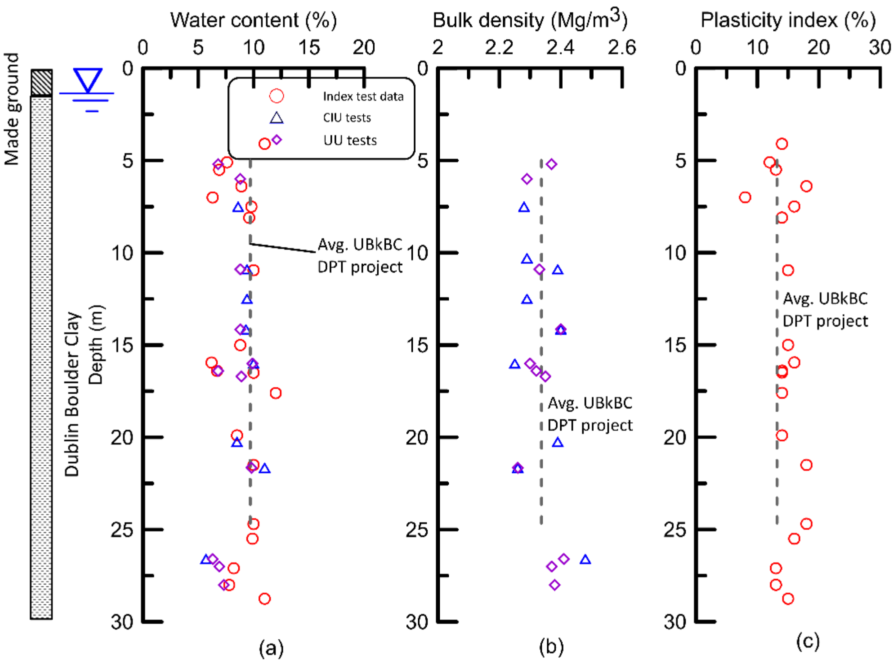

Figure 3. Index properties for Dublin Boulder Clay at the location of the HPD tests (a) water content, (b) density and (c) plasticity index

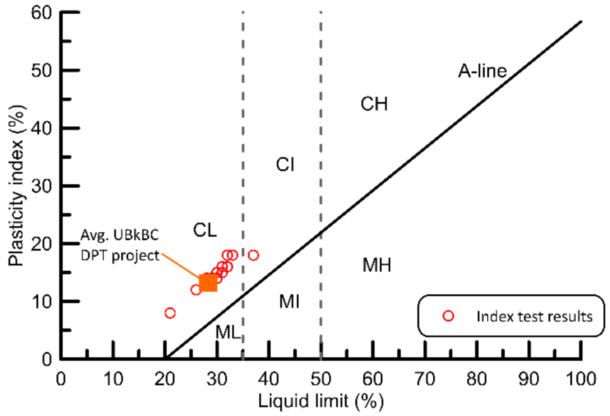

Figure 4. Plasticity chart

Some index data in the form of water content (w), bulk density (ρ_b) and plasticity index (I_p) are shown on Figure 3. The test data is compared with average values from the Upper Black Boulder Clay (UBkBC) at the very well characterized Dublin Port Tunnel (DPT) site (Long and Menkiti 2007b).

None of the index properties presented on Figure 3 show any pattern versus depth. The values are similar at all depths. The average water content of the material is very low at about 8.5%. Correspondingly the material shows a very high bulk density of about 2.34 Mg/m^3, not too far from that of concrete. There is no clear difference between the results from basic index testing or from consolidated undrained (CIU) or unconsolidated undrained triaxial testing (UU). These values are very close to that of the UBkBC at the DPT site. The plasticity chart, shown on Figure 4, confirms that the material is again very similar (albeit with slightly higher plasticity) to that at the DPT site with an average I_p of 14.5%, indicating that the material is of low plasticity.

Particle size distribution charts for the material are shown on Figure 5 and are again compared to values for the UBkBC at the DPT site. The curves show the classical straight line dimictic profile, which is typical of a glacial till (Clarke 2018). Most of the curves fall within the range for the DPT UBkBC with some being on the slightly finer side. Average fines content is some 49%.

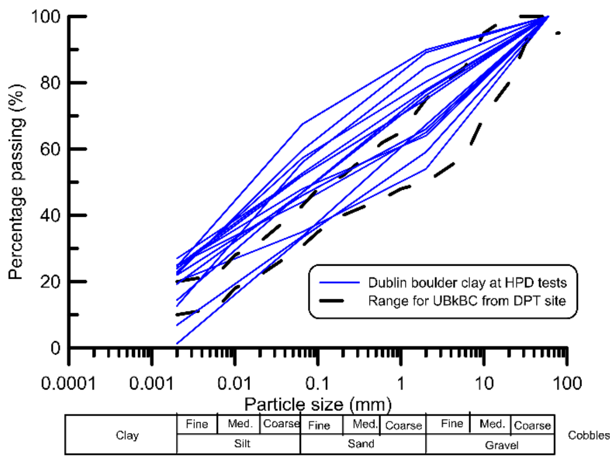

Figure 5. Particle size distribution curves

3.2. Strength parameters

Some strength related properties for the material at the location and depth of the HPD tests are shown on Figure 6 in the form of liquidity index, undrained shear strength from UU tests and the results of standard penetration tests (SPT).

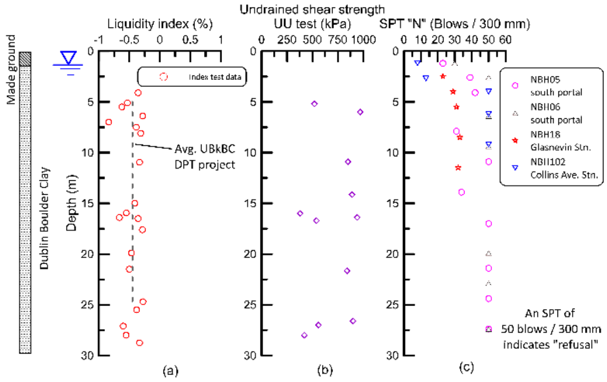

Figure 6. Results of strength related tests (a) liquidity index, (b) s_u from UU tests and (c) standard penetration test results

Liquidity index [I_L = (w-w_P)/I_p; where w_P is the plastic limit] can sometimes be a very useful parameter for distinguishing between different strata and giving some indication of the degree of overconsolidation of the material. Long and Menkiti (2007a) studied the I_L values for 6 Dublin sites, including the DPT and showed that for the UBkBC values are usually constant with depth and fall in the range –0.4 to –0.5. Similar values are found here. Hanrahan (1977) collated I_L values for several Irish tills and found that Dublin till has average value of about –0.5 as found here. He also pointed out that the Dublin tills are particularly noteworthy for having I_L below zero.

These strongly negative values reflect the highly "overconsolidated" state of the material.

It has been shown by several authors (Farrell 2024; Long and Menkiti 2007b) that UU triaxial tests on DBC will give similar results to CIU tests provided the tests are carried out on high quality samples, e.g. Geobore S. UU test results shown on Figure 6b show a significant scatter in the data, which is likely to be due to the high content of coarse particles. Nevertheless the values indicated that the material is of "very stiff" to "hard" consistency.

Except for some meaningful results at relatively shallow depths, it can be seen on Figure 6c that many of the SPT values often refuse in the DBC.

4. HPD test technique

4.1. Operating technique

The HPD is a cylindrical 95 mm diameter probe which is inserted into a cored 99 mm diameter test pocket, drilled using a T6-H-size core barrel. The HPD is therefore termed a pre-bored type instrument. The probe, approximately 1.5 m in length, has a central section which is covered by a rubber membrane. Pressure applied to the inside of the instrument, via compressed air, forces the membrane to expand against the test pocket wall. The radial displacement of the inside boundary of the membrane is measured at six points equally distributed around the centre of the expanding section, by free moving arms. This displacement, and the pressure necessary to cause the movement, is continuously monitored by transducers contained within the instrument. The HPD is linked to the ground surface via a combined pressure hose and electrical power / communication umbilical cable which connects the instrument to the pressure source and readout unit. The tests on this project were performed using a probe manufactured by Cambridge InSitu Ltd.

The boreholes were constructed using a rotary drilling rig by conventional rotary coring at nominal 146 mm diameter, using water flush, to approximately 1.5 m above the scheduled pressuremeter test depth. A 2 m to 3 m long section was then drilled using a T6-H size core barrel to provide a test pocket of nominal diameter 99.2mm. The HPD was inserted into the test pocket as soon as practicably possible in an attempt to minimize stress relief. During the tests a number of unload-reload loops were performed. Before carrying out the loops a short holding period was maintained to allow reduction of creep on the ground.

Test loading continued until it was evident that that material yield had been induced in the clay, with the following pressure-displacement curve moving to shallow gradients. Finally the probe was unloaded and removed from the test pocket.

4.2. Challenges in testing DBC

A significant issue with undertaking tests in the DBC is the formation of suitable test pockets. Whilst the ‘hard’ nature of the DBC means that conventional rotary coring techniques work well, the presence of coarse gravel and cobbles within the matrix can be problematic. During coring of the test pocket, incomplete removal of coarse particles can result in scouring and overcoring with the resulting test pocket wall being oversize, rough, out of gauge, and often voided.

In addition, the common presence of coarse particles within the material being tested at the probe-wall interface can result in unequal, non-circumferential expansion of the probe membrane, which can hinder subsequent test interpretation.

4.3. Analysis of HPD data

4.3.1. General

The interpretation of the HPD tests follows industry standard methods (Mair and Wood 1987; Clarke 1996). An example test curve is shown on Figure 7. A valid assumption often made in pressuremeter tests carried out in clay, is that the response is undrained. Previous undrained analysis of tests in the DBC has resulted in excessively high undrained shear strengths, typically in the range 1.0 to 1.8 MPa, with a median average value of 1.4MPa.

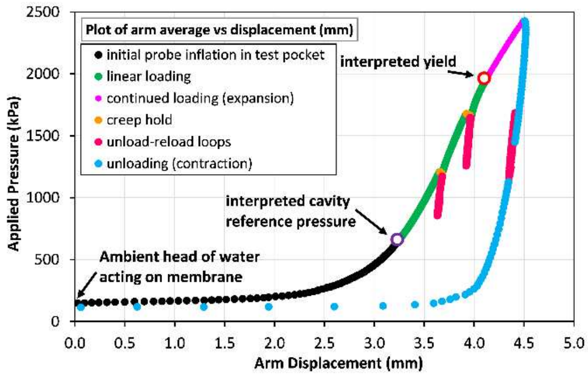

Figure 7. Example pressuremeter test curve

In reality, the behaviour of the DBC during loading is better viewed as a drained event as it could be seen that during the test the membrane loses contact with the borehole wall due to the rough edges of the pocket. In addition, the observation that stiffness increases with increasing stress is indicative of drained loading.

4.3.2. In situ coefficient of horizontal stress (K_0)

The interpretation of K_0 relies upon an accurate estimation of in situ horizontal stress. This is tentative at best from HPD test data, simply due to stress relief and probable disturbance to material during drilling of the test pocket. In the absence of other test methods, such as use of a self-boring pressuremeter, which is close to impossible in the DBC, an approximation of horizontal stress can be attempted via the cavity reference pressure (p_o), whereby during initial loading of the probe in the test pocket the displacement arms start to show a linear response. Figure 8 shows the issue with HPD data in that the arm response is typically variable throughout initial expansion in an effective void, prior to meeting the pocket wall, followed by the effective resistance of the ground to loading resulting in the onset of a linear loading response, as the cavity reference pressure is exceeded.

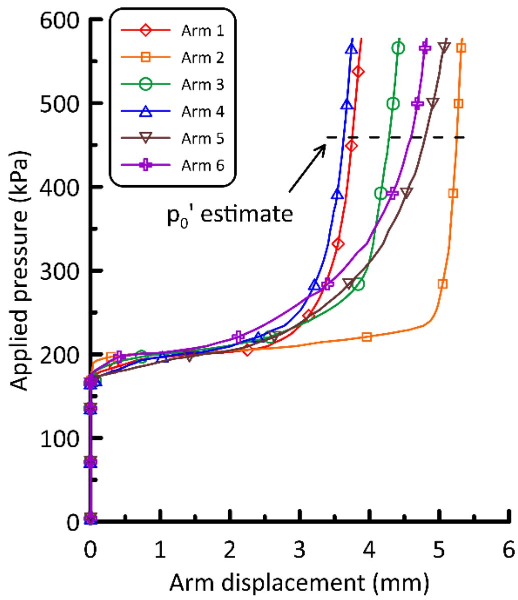

Figure 8. Pressuremeter displacement arm response

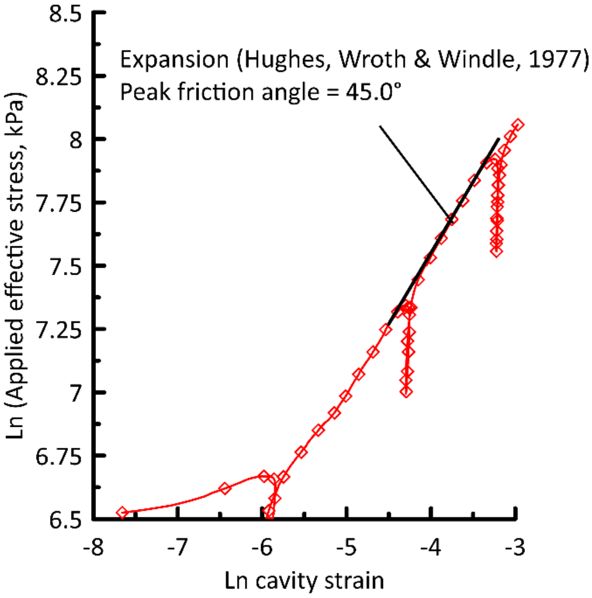

Figure 9. Friction angle example

Estimation of p_o in the example shown on Figure 8 could be made from the least disturbed, stiffer response shown by arms 1 to 4, from around 320 to 350 kPa. Arms 5 and 6 show expansion in a 'softer' zone in the pocket, likely due to drilling induced disturbance.

4.3.3. Peak angle of shearing resistance (ϕ_{peak})

Drained analysis on the expansion or loading curve has been carried out using the method of Hughes, Wroth, and Windle (1977). A plot on log scales of effective applied pressure against cavity strain should provide a linear relationship, from which derivation of the peak angle of shearing resistance friction can be made. An assumed value of 24° for the critical state angle of shearing resistance required for the derivation has been used. An example plot is shown in Figure 9.

A similar calculation can be attempted out on the contraction or unloading section of the test via the method of Houlsby, Clarke, and Wroth (1986). In a similar manner to the expansion method, a linear trend on a log scale plot of effective pressure and cavity strain parameters allows derivation of the peak angle of shearing resistance. Unfortunately, in the material described here, the contraction behaviour is considered far from plastic, and in addition based on the strength of the material, it is likely that probe is not in full contact with the test cavity pocket wall during the full unloading period. It is perhaps fortuitous that similar values of angles of shearing resistance to those derived from the loading analysis can be determined.

4.3.4. Shear modulus

Shear modulus values, derived from the initial loading after overcoming the cavity pressure in a HPD test, should always be discounted due to stress relief and almost inevitable disturbance during test pocket formation. They are typically an order of magnitude lower than moduli values derived from analysis of unload-reload loops carried out along the expansion and contraction paths.

Shear modulus values derived from the linear interpretation of the unload reload loops confirm a drained response of the DBC (in addition to the observation of loss of contact between the membrane and the rough pocket wall), with increasing modulus values with increasing stress.

5. Results of HPD test

5.1. In situ coefficient of horizontal stress (K_0)

Values of K_0 obtained from HPD are shown on Figure 10b. There appears to be two groups of results. Above 8 m depth the values are relatively high, being on average 2.5. Below this depth the values approach an average value of 1.0. Previous work in the laboratory (Long and Menkiti 2007b) and in the field using geophysical testing (Long et al. 2025) indicate K_0 values close to 1.0. Typically values of 1.0 to 1.5 are commonly used in design practice, e.g. of embedded retaining walls.

The reasons for the high values above 8 m depth are not clear.

5.2. Peak angle of shearing resistance

Values of ϕ'_{peak} derived from HPD tests are compared to the range of values for DBC, determined from triaxial tests outlined by Long and Menkiti (2007b) in Figure 10a ϕ'_{peak} values fall within the range previously derived from triaxial testing. Effective cohesion (c') is normally assumed to be equal to zero in DBC.

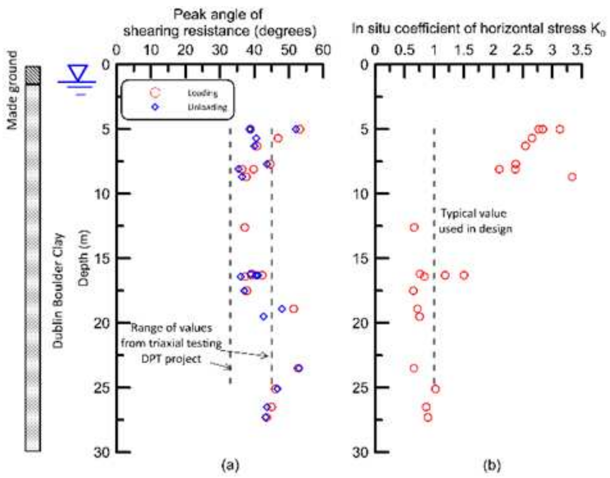

Figure 10. Results of HPD test analysis (a) peak angle of shearing resistance and (b) in situ coefficient of horizontal stress (K_0)

5.3. Shear modulus

A non-linear drained interpretation of the unload-reload loops provides secant shear modulus values at varying strain levels. The derived exponent of non-linearity (β) is variable, typically ranging from 0.7 to 0.8, with a median value of 0.76, consistent with the very high strength to hard DBC. A plot of secant modulus data at 0.1, 0.01 and 0.001% shear strain, obtained from loops on the loading path, shown on Figure 11, illustrates a slight trend of increasing modulus with depth. Perhaps not surprisingly there is considerable scatter in the data and there seems to be no clear pattern in the values versus depth. Nonethless the 0.001% strain values are relatively consistent with a typical small strain stiffness which could be calculated assuming the shear wave velocity V_s is 500 m/s (Long et al. 2025). In practical design a shear stiffness value of 33 MPa often assumed for elastic stiffness of the DBC under drained conditions (Drained Young's modulus = 80 MPa) and this value is at the lower end of the 0.01% shear strain data.

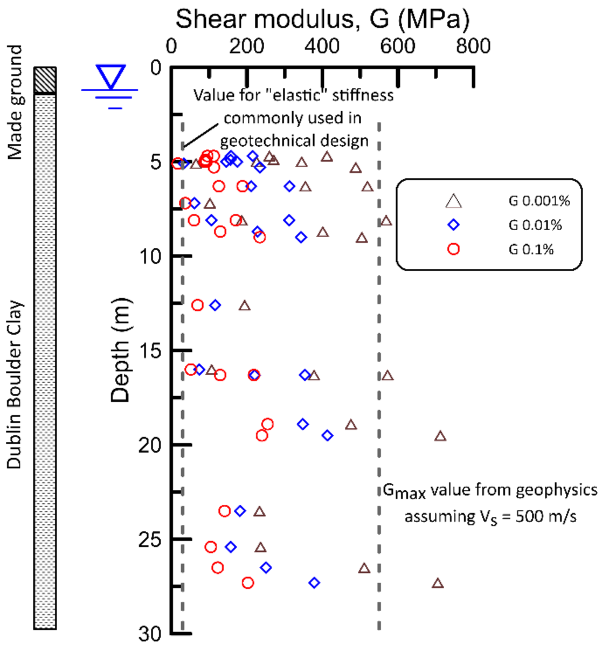

Figure 11. Shear stiffness at various strain levels.

6. Conclusions

The purpose of this paper is to summarise HPD tests on Dublin Boulder Clay, a material which is very difficult to test in situ due to its high strength and high coarse particle content. Some conclusions from the study are as follows:

- The testing was carried out over a wide area of Central and north Dublin but the index properties of the DBC are consistent across the area. Average water content, density, plasticity index and fines content are 8.5%, 2.34 Mg/m^3, 14.5% and 49% respectively.
- A significant issue with undertaking tests in the DBC is the formation of suitable test pockets. A careful assessment of the response of each of the displacement arms needs to be made and unreliable data omitted.
- Previous analysis of HPD testing in the material had assumed an undrained response. However, it is considered that drained behaviour better represents the tests and this is evident in the gap which formed around the membrane and the increase in shear stiffness with increasing stress.
- Values of K_0 above 8 m are higher than those conventionally used in design. Those below 8 m, which are in the range of 1.0 to 1.5, are similar to those usually adopted. The reason for the differences is not clear.
- Values of angle of shearing resistance and predictions of shear stiffness are consistent with those obtained from other methods.
- Further use of the test seems well warranted. It would be useful to compare the HPD data with that which could be back-analysed from a full scale deep excavation.

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