

Estimation of the small strain stiffness of glacial till using geophysical methods and barometric loading response



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ABSTRACT

Stiffness values in geotechnical structures can range over many orders of magnitude for relatively small operational strains. The typical strain levels where soil stiffness changes most dramatically is in the range 0.01-0.1%, however soils do not exhibit linear stress-strain behaviour at small strains. Knowledge of the *in situ* stiffness at small strain is important in geotechnical numerical modelling and design. The stress-strain regime of cut slopes is complex, as we have different principle stress directions at different positions along the potential failure plane. For example, loading may be primarily in extension near the toe of the slope, while compressive loading is predominant at the crest of a slope. Cuttings in heavily overconsolidated clays are known to be susceptible to progressive failure and subsequent strain softening, in which progressive yielding propagates from the toe towards the crest of the slope over time. In order to gain a better understanding of the rate of softening it would be advantageous to measure changes in small strain stiffness in the field. Seismic geophysical surveys result in very small strains and have been shown to provide estimates of small strain elastic moduli. Furthermore, loading efficiency theory uses the pore pressure response of grouted piezometers to barometric pressure fluctuations to estimate the compressibility of the formation. Barometric loading efficiency gives a direct measure of stiffness from continuous monitoring of pore pressures, whilst seismic surveys provides a means of mapping stiffness values both spatially, and temporally. This paper outlines the techniques used to investigate small strain stiffness in a glacial till cutting in Northern Ireland, using seismic surveys and barometric loading efficiency theory and presents some preliminary findings.

RÉSUMÉ

La valeur du module de cisaillement dans des ouvrages géotechniques peut varier de plusieurs ordres de grandeur pour des déformations relativement petites. Les niveaux de déformation, pour lesquels le module de cisaillement varie drastiquement, sont typiquement compris entre 0.01-0.1% ; pourtant, les sols ne sont pas caractérisés par une relation contrainte-déformation linéaire pour des petites déformations. La connaissance du module de cisaillement *in situ* pour de petites déformations est importante pour la modélisation numérique et la conception en géotechnique. Le comportement contrainte-déformation des pentes artificielles est complexe, car il peut y avoir plusieurs directions principales de contrainte à des positions différentes le long du plan de rupture potentiel. Par exemple, le chargement est principalement en tension près du pied de la pente, tandis que le chargement en compression est prédominant au sommet de la pente. Les talus en argile surconsolidée sont souvent prédisposés à des phénomènes de glissement progressif et donc d'écrouissage, où l'affaissement progressif se propage du pied vers le sommet de la pente dans le temps. Afin d'obtenir une meilleure compréhension de la vitesse d'écrouissage, il est avantageux de mesurer les variations du module de cisaillement du sol sur le terrain. Les relevés sismiques produisent des petites déformations et permettent d'obtenir une estimation des modules élastiques en petites déformations. En outre, la théorie de l'efficacité de chargement utilise la réponse de la pression interstitielle (mesurée par des piézomètres) aux fluctuations de la pression barométrique pour estimer la compressibilité du sol. L'efficacité du chargement barométrique donne donc une estimation directe de la rigidité du sol à partir de la vérification continue de la pression interstitielle; par contre, les levés sismiques permettent de mesurer la rigidité du sol spatialement et temporellement. Cet article décrit les techniques utilisées pour étudier la rigidité du sol en petites déformations d'une pente artificielle dans une moraine glaciaire en Irlande du Nord ; des relevés sismiques et la théorie de l'efficacité de chargement barométrique. Des résultats préliminaires y sont aussi présentés.

1 INTRODUCTION

The road network in Northern Ireland encompasses a substantial number of large cuttings in heavily overconsolidated stiff natural clays of lodgement till. The stress-strain regime of these cut slopes are complex with different principle stress directions at different positions along the potential failure plane. For example, loading may be primarily in extension near the toe of the slope,

while compressive loading is predominant at the crest of a slope (Figure 1).

Cuttings in overconsolidated clay are known to be susceptible to progressive failure, with softening of the toe and the development of a rupture surface into the slope, as is well documented for London Clays (Potts, 1997). In literature, this mechanism of progressive, or delayed, failure has been attributed to a range of factors, including dissipation of the negative pore water pressures (pwp)

generated during an excavation, and the strain softening nature of the overconsolidated till (Hughes et al., 2007). Consequently, the long-term stability of infrastructure cuttings in lodgement tills may be susceptible to this failure mechanism. Therefore a means of assessing the change in stiffness over time would be a useful indicator of slope condition for geotechnical asset owners.

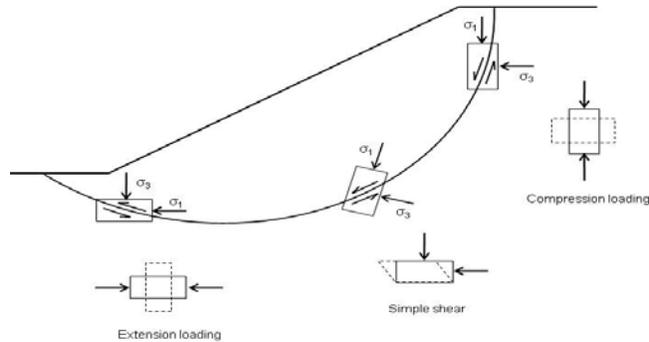


Figure 1: Principal stress regime in a cutting (after Carse, 2014)

Laboratory testing on reconstituted samples of tills has been carried out to investigate this time-dependent behaviour of Northern Irish till. It is important to determine not only the driving factor behind progressive failure, such as pore water pressure dynamics, but to determine whether the soil undergoes viscoplastic straining (creep) simply due to elevated stress conditions (current in situ stress states) at rest. Research has shown that under elevated constant deviator stresses (70-90% peak strength), close to critical state, the till can accumulate a significant amount of shear strain due to pore water pressure cycling of $\pm 5\text{kPa}$ (Harley et al., 2014). Furthermore, the till may also reach its ultimate state simply by creeping when held under constant effective stress conditions close to failure (Carse, 2014; Harley et al., 2014).

Laboratory observations show that clay dominated tills can creep, and that the creep rate will increase depending on how much a material has softened, and the magnitude and number of pwp cycles it experiences. However, laboratory testing is not a practical means of obtaining information on soil stiffness under field conditions. Sample disturbance is known to cause large changes in soil stiffness (Clayton, 2011) and the stoney nature of these tills also makes sampling and testing of “undisturbed” samples particularly problematic.

If till cuttings do undergo progressive failure, changes in stiffness (e.g. softening) should be reflected in commensurate temporal and spatial changes in stiffness and strength. Change in stiffness is therefore one key parameters controlling deformation of the slope. In order to gain a better understanding of the rate of softening one approach would be to monitor changes in small strain stiffness in the field using non-invasive techniques.

The velocities at which shear and compression waves propagate through soil are dependent on small strain stiffness and have been shown to provide estimates of

small strain elastic moduli. Loading efficiency uses the pore pressure response of grouted piezometers to barometric pressure fluctuations to estimate the compressibility of the formation (Smith et al., 2013). An estimation of small strain stiffness from both of these techniques will be presented in this paper.

2 RESEARCH SITE

The research site used for this study is near Loughbrickland in Northern Ireland (Figure 2). The site was identified as a potential risk due to a sequence of failures at Dromore along the A1 Belfast-Newry dual carriageway, in similar geological settings (Hughes et al. 2007). The factors postulated for this failure were a long-term strength reduction due to progressive deformations, strain softening and the dissipation of excess pore water pressures generated during excavation.



Figure 2: Location of Research Sites

Loughbrickland cutting is 25m high, with a slope angle of approximately 26° . It was excavated in 2004 to improve the horizontal realignment of the A1 carriageway. The soil profile comprises of completely to moderately weathered Greywacke sandstone with completely weathered slaty mudstone interbeds, which are typical of the Gala Group bedrock geology of the area (Anderson, 2004). This is overlain by a lower till layer, and an upper till layer with a weathered zone (Figure 5). The site is fully instrumented to monitor pore water pressures at a variety of depths, surface water balance and infiltration, water table elevation and meteorological conditions. For more detail on the site see (Clarke, 2007; Carse, 2014; McLernon, 2014).

3 METHODOLOGY

It is common practice to deduce small strain elastic properties in the triaxial by installing bender elements, however even undisturbed samples of soils tested in this manner are subject to massive disturbance, Alternative methods and therefore required to determine the *in situ* stiffness of the glacial till.

3.1 Seismic Surveys

Seismic geophysical surveys result in very small strains and have been shown to provide estimates of small strain elastic moduli (Whiteley, 1994; Soupios et al., 2006; Long and Menkiti, 2007; Clayton, 2001). It has also been shown that laboratory stiffness levels are similar to field seismic measurements (Michaels, 1998; Clayton, 2011).

When investigating compressibility of a formation, S-waves should be extracted directly as they are independent of the position of the water table. A series of seismic surveys were conducted at the Loughbrickland site, namely Multichannel analysis of surface waves (MASW) and P-wave refraction tomography. Both methods involve the recording of the vertical vibrations of the soil generated by an active seismic source, and the vibrations are acquired by means of a set of vertically polarised geophones placed at the top surface of the subsoil (Figure 3).



Figure 3: Picture showing the layout of the geophones at the crest, berm and toe of the Loughbrickland cutting

For the MASW technique, the acquisition stage aims at recording the propagation of surface waves (and here specifically Rayleigh waves) in the shallow subsurface. In a vertically heterogeneous medium (as the tills are) Rayleigh waves exhibit a dispersive behaviour, i.e. the phase velocity of the various frequency components depends on the frequency itself. Rayleigh waves propagate in a portion of subsurface comprised between the soil surface and a depth approximately equal to one wavelength: as the wavelength depends on the frequency, different frequency components propagate through different layers and hence exhibit different phase velocities. The acquired seismic section is therefore processed to provide information about the dispersion characteristics of Rayleigh waves. As the phase velocity of Rayleigh waves depends predominantly on the S-wave velocity (V_s) model of the subsoil, surface wave dispersion data can be inverted to reconstruct the V_s profile of the near-surface beneath the recording array (Socco and Strobbia, 2004). The adopted inversion approach is a Monte Carlo inversion procedure as developed by Maraschini and Foti (2010). From the retrieved S-wave velocity profile it is possible to derive the distribution of the small strain shear modulus in the subsoil (Foti, 2003). However, a bulk density and

Poisson's ratio must be assumed for the soil layer. The transect locations are shown in Figure 4.

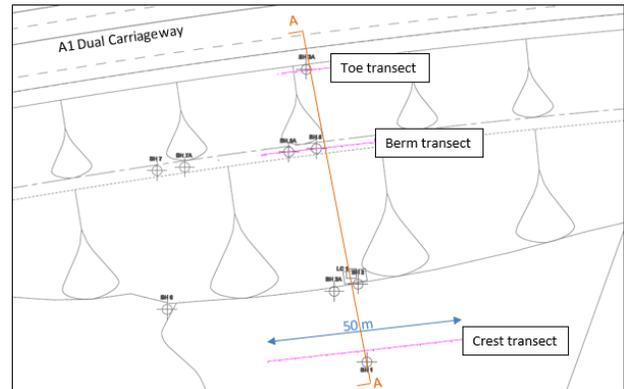


Figure 4: Transect locations for seismic refraction surveys and borehole locations on the Loughbrickland cutting

In order to deduce an accurate estimate of Poisson's ratio, using the relationship between V_s and V_p profiles correlates to a Poisson's ratio. In the case of Loughbrickland a ratio of $V_s = 0.3V_p$ corresponds to a Poisson's ratio (ν) of 0.45; small strain stiffness is typically found at $\nu = 0.4-0.45$. The following equations can be used to deduce the shear modulus, and therefore Young's modulus:

$$G = \rho_b V_s^2 \quad [1]$$

$$E = \frac{G}{2(1+\nu)} \quad [2]$$

For an S-wave velocity (V_s) of 360 m/s, corresponding to a P-wave velocity (V_p) of approximately 1200 m/s, which gives a Poisson's ratio of 0.45. This represents a strata with a shear modulus, G , of 246 MPa (assuming a density of 1900 kg/m^3) which gives a Young's Modulus, E of 714 MPa. A stiffness vs depth profile from a survey transect along the berm of the slope is shown in Figure 6.

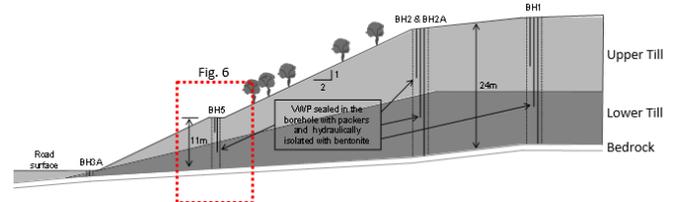


Figure 5: Cross-section A-A of cutting at Loughbrickland, Northern Ireland showing instrumentation locations, geological cross-section and the survey transect location used to deduce a stiffness profile with depth (see Fig. 6).

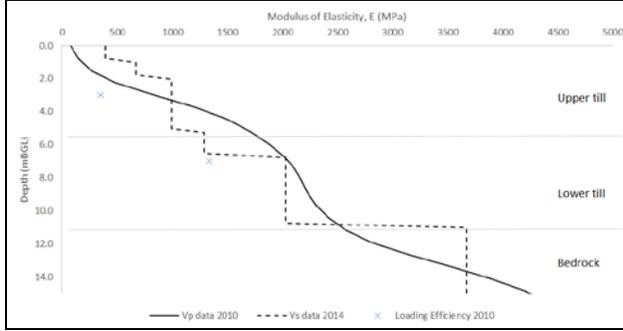


Figure 6: Modulus of Elasticity with depth at the berm (see Figure 5) of the cutting at Loughbrickland, Northern Ireland as deduced from P-wave data and loading efficiency values in 2010 (Carse, 2014), and S-wave data in 2014.

3.2 Loading Efficiency

Boreholes are often installed on sites to monitor pore water pressure deep within a soil formation. It is common knowledge that barometric changes at the ground surface will be reflected in changes of pwp, and it is common practice to deduct the barometric pressure from the pwp recorded at depth to get a 'corrected' pwp. However, more recently it has been shown that the pwp response to barometric changes can be used for a secondary purpose, to quantify compressibility of the formation with depth (Smith et al., 2013).

Changes in barometric pressure will cause an undrained pwp response in the same way as any imposed load on the surface would (Jacob, 1940). This 'loading efficiency' theory uses the pwp response of grouted piezometers to barometric pressure fluctuations to estimate the compressibility of a formation, and thus can be used to deduce the small strain stiffness. When analysing the undrained shear strength of soils Skempton (1954) used the known principal stresses to determine changes in pore water pressure in the triaxial cell as outlined in Eqn. 3-7. The formulation assumes the pore fluid incompressible; therefore assuming a change in pwp will always equal the change in applied total stress. From this we have the pore pressure coefficients A and B, commonly used today:

If $\Delta p = 0$,

$$\Delta p - \Delta u = 0 \quad [3]$$

$$\Delta u = \Delta p = \frac{\Delta \sigma_1 + \Delta \sigma_2}{2} \quad [4]$$

$$\Delta u = \left[\frac{\Delta q}{2} + \Delta \sigma_3 \right] \quad [5]$$

$$\Delta u = B[\Delta \sigma_3 + A(\Delta \sigma_1 - \Delta \sigma_2)] \quad [6]$$

Where B=1 if saturated, A = 1/3 if isotropic elastic.

$$\Delta u = B[\Delta \sigma_3 + A(\Delta q)] \quad [7]$$

In laboratory testing, the coefficients are determined from volume change characteristics and soil compressibility, where, B=1 if fully saturated, A = 1/3 if isotropic elastic and A \neq 1/3 if anisotropic. However, in the event that pore pressure changes are monitored, the relationship can be rearranged to solve for the constrained elastic pore pressure coefficient if we assume zero lateral strain.

Skempton's constrained elastic pore pressure coefficient is the ratio of vertical stress change at depth (Δu) attributed to barometric pressure change at the surface ($\Delta \sigma_1$), i.e. the loading efficiency (\bar{B}). Eqn. 7 can therefore be divided through and rearranged to give Eqn. 9.

$$\bar{B} = \frac{\Delta u}{\Delta \sigma_1} \quad [8]$$

$$\bar{B} = B \left[1 - (1-A) \left(1 - \frac{\Delta \sigma_2}{\Delta \sigma_1} \right) \right] \quad [9]$$

The pwp changes monitored at depth in saturated soil formations can therefore be used to determine insitu stiffness values. The compressibility of the formation can be calculated by assuming the pore compressibility and the known barometric pressure fluctuations from theory by Jacob (1940), later used by Rojstaczer (1988), van der Kamp (1997) and Smith et al. (2013):

$$\bar{B} = \frac{1/E_c}{(1/E_c + n\beta)} \quad [10]$$

$$\frac{1}{E_c} = m_v = \alpha \quad [11]$$

$$\bar{B} = \frac{\alpha}{\alpha + n\beta} \quad [12]$$

$$\alpha = \frac{n\beta\bar{B}}{1-\bar{B}} \quad [13]$$

Where $1/E_c$ is the drained constrained modulus of elasticity (1D volume compressibility, m_v in soil mechanics, α in hydrogeology; see Eqn. 11), n is the porosity of the soil formation from laboratory testing ($n=0.18$) and β is the compressibility of water ($\beta = 4.7 \times 10^{-10} \text{ Pa}^{-1}$ at 25°C). This relationship (Eqn. 12) makes a number of assumptions; that soil particles are incompressible compared with compressibility of water,

Table 1. Summary of S-wave velocities, loading efficiencies and stiffness with depth.

Depth (mBGL)	Layer	S-wave Velocity, Vs (m/s) ⁺	Loading Efficiency ⁺⁺	Young's Modulus, E (MPa)
Toe				
0-3.5	Lower Till	230-454	-	291-1138
3.5	Bedrock	486	-	1510
Berm				
0-5.5	Upper Till	260-470	-	250-1000
3	Upper Till	-	0.95	350
5.5-11	Lower Till	470-591	-	1000-2500
7	Lower Till	-	0.7	1336
11	Bedrock	796	-	3500
Crest				
0-12	Upper Till	190-345	-	633-114
7	Upper Till	-	0.7	1336
9	Upper Till	-	0.6	2077
12-24	Lower Till	709-826	-	2353-2741
16	Lower Till	-	0.6	2077
24	Bedrock	1276	--	4234

⁺Assumed density of 1900 kg/m³

⁺⁺Assumed porosity of 0.18, Poisson's ratio of 0.45 and compressibility of water of 4.7 x 10⁻¹⁰ Pa⁻¹ at 25°C

and therefore volume change occurs only within the pore spaces, therefore overall volume change is negligible.

Using Eqn. 13, E_c can be used to deduce small strain stiffness using Eqn. 14 from Poulos and Davis (1974):

$$E = \frac{E_c(1+\nu)(1-2\nu)}{(1-\nu)} \quad [14]$$

To determine the loading efficiency at the depth of each transducer, the pwp at depth and the barometric pressure at the surface are logged simultaneously, and therefore provide a means of assessing how much each varies with the other. The change in barometric pressure is multiplied by a number varying between 0-1 ($\bar{\beta}$) and is subtracted from the raw pwp data. The resulting trends are superimposed to visually determine $\bar{\beta}$, which is judged to produce the 'smoothest' corrected pressure record with the least variation between precipitation events (Smith et al., 2013).

As an example, a piezometer at a depth of 7m has a loading efficiency ($\bar{\beta}$) of 0.7 as deduced from monitored pwp and barometric pressure data. For a porosity of 0.18, assuming the compressibility of water to be 4.7x10⁻¹⁰Pa⁻¹ and a Poisson's ratio of 0.45, determine the compressibility of the formation and therefore Young's Modulus, E.

$$\alpha = \frac{n\beta\bar{\beta}}{1-\bar{\beta}} = \frac{0.18 \times 4.7e^{-10} \times 0.7}{1-0.7} = 1.9e^{-10} \quad [15]$$

$$E_c = \frac{1}{\alpha} = \frac{1}{1.9e^{-10}} = 5.7e^9 \quad [16]$$

$$E = \frac{E_c(1+\nu)(1-2\nu)}{(1-\nu)} \quad [17]$$

$$E = \frac{5.7e^9(1+0.45)(1-0.9)}{(1-0.45)} = 1335MPa \quad [18]$$

4 RESULTS SUMMARY

Values of stiffness estimated using both the seismic refraction and the loading efficiency method are presented in Table 1. A general trend is that stiffness increases with depth, and the values are comparable to similar sites across Northern Ireland (Carse, 2014). The depths presented from loading efficiency represent the piezometer tip depth, and the other depth ranges are categorised based on borehole logs.

The range of stiffness presented in this paper shows that the glacial till in Northern Ireland has much higher minimum stiffness than that of the London clay for example; Clayton (2001) places the small strain undrained stiffness of London clay at 240MPa. It also shows that it is comparable, if a little less stiff, than the Dublin boulder clay; Long and Menkiti (2007) places E at approximately 750-4200 MPa, with an assumed Poisson's ratio of 0.4.

5 CONCLUSION

Small strain stiffness is an important parameter required to numerically model deformation, however it is a difficult parameter to measure both in the laboratory and in the

field. This paper has presented two alternative methods for estimating *in situ* stiffness, using seismic refraction analysis and the loading efficiency of the formation in response to changes in barometric pressure.

Due to the predicted more acute climate scenarios in the future, as presented by UK Climate Projection 09 (Murphy et al., 2009), the variation and magnitude of pore pressure cycles are likely to be more severe, putting cuttings in till at greater risk. By continuing a field campaign of seismic surveys and comparing these against long-term monitoring of pore water and barometric pressures at specific sites to assess small strain stiffness changes in slopes it could help provide another indicator of long-term slope condition and enable changes in stiffness *in situ* to be monitored, and observe the rate of softening in the till.

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