Elasticity and plasticity of Palaeogene clay from Fehmarn Belt area

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Summary

Ten naturally saturated Palaeogene clay samples were examined and analysed in terms of their physical and geotechnical properties. The geotechnical deformation properties and ultrasonic wave velocity were measured simultaneously during uniaxial confined compression stress testing. The obtained results indicate that the deformation of the studied Palaeogene clay is plastic in the sense that water is squeezed out during loading, but elastic in the sense that water is sucked back during unloading. Our results can aid in the estimation of drained elastic parameters from bulk density and velocity of elastic waves and thus may have implications in engineering practice.

Introduction

Extensive site investigations were carried out to help the design and construction of a tunnel through Fehmarn Belt between Denmark and Germany. Comprehensive laboratory tests were done by geotechnical consulting companies, but ten Palaeogene clay samples were selected and used here to study the relation between plastic and elastic properties of Palaeogene clay.

Shrink-swell behaviour of clay can cause major damage to structures above or below ground (Jones & Terrington 2011), and it has been found that when naturally water saturated Palaeogene clay is mounted in an oedometer cell without access to water and loaded to its in-situ vertical effective stress and then given access to its native salt pore water, the clay absorbs water and swells (Jessen et al. 2011). This behaviour indicates that the Palaeogene clay in nature should expand at its mean effective in-situ stress, provided natural water is available. A study by Krogsbøll et al. (2012) on Palaeogene clay from Fehmarn Belt provides clues that elasticity plays a larger role than usually assumed even at high strains. Therefore in this study, we focus on the elastic properties of the naturally water saturated Palaeogene clay. We used geotechnical data and ultrasonic velocity data to estimate the elasticity and relate it to strain caused by mechanical loading. We aimed to see whether we can explain the deformation behaviour from elasticity alone.

Methods

Ten preserved naturally water saturated core plugs of 37.5 mm in diameter and nominally 25 mm long were cut from the intact Palaeogene clay cores. The laboratory measurements were done in drained uniaxial strain condition using a triaxial Hoek cell.
We used a stress path simulating uniaxial strain condition ($K_o$ geotechnical stress condition) which confers to area-constant cross section during uploading and unloading. This uniaxial strain condition is equivalent to the oedometer cell stress condition, so we obtain the geotechnical oedometer modulus, $M_{\text{drain}}$. The stress path applied is then used stepwise with sufficiently long time steps to allow for consolidation of the test specimen in the Hoek cell and at end of each step the velocity $V_p$ of a 200 kHz compressional elastic wave was determined, and from $V_p$ and bulk density, $\rho_b$ we obtain the P-wave modulus ($M_{\text{sat}}$) representing elastic deformation in the undrained state. The ratio of the confining stress (radial stress) to the axial stress was determined based on the values of the coefficient of earth pressure at rest ($K_o = 0.55$) reported by Jessen et al. (2011). $M_{\text{drain}}$ of each sample was determined on a series of selected slopes on the loading as well as the unloading curve. We expect that $M_{\text{drain}}$ include contingents from both elastic and inelastic deformation, and in order to estimate the elastic contribution, we wish to compare $M_{\text{drain}}$ to the purely elastic modulus of uniaxial strain under drained conditions, $M_{\text{dry}}$, as estimated from $M_{\text{sat}}$, porosity ($\phi$) and mineral modulus ($M_{\text{grain}}$) according to approximated Gassmann’s equation (Mavko et al. 1998):

$$M_{\text{dry}} \approx M_{\text{sat}} \left( \frac{\phi M_{\text{grain}}}{M_{\text{fl}}} + 1 - \phi \right) - M_{\text{grain}} \left( \frac{\phi M_{\text{grain}}}{M_{\text{fl}}} + M_{\text{sat}} / M_{\text{grain}} - 1 + \phi \right),$$

where $M_{\text{fl}}$ is the P-wave modulus for the pore water which in the present case is close to 2.4 GPa. In order to do this, we must first establish the mineral modulus for uniaxial strain ($M_{\text{grain}}$). In general, moduli of uniaxial strain are higher than Young’s modulus, which describes deformation under uniaxial stress, so we assumed that Young’s modulus of grains represents a lower bound for $M_{\text{grain}}$. Young’s modulus of grains ($E$), in GPa, can be estimated from grain density ($\rho_g$), in kg/m$^3$, according to the correlation of Chen & Evans (2006):

$$E = -377 + 0.189 \rho_g.$$

**Results**

Results of the mechanical loading of the naturally water-saturated Palaeogene clays, subjected to a maximum of 3 MPa uniaxial stress, are displayed in Figure 1. This figure illustrates the drained behaviour of the studied Palaeogene clays. Generally, the studied Palaeogene clays are deformed little and retained high porosity along the whole stress path from 0.2 to 3.0 MPa. This means the pore-water expels slowly due to the low permeability. Generally, this agrees with the compaction behaviour of smectite-rich clays of Mondol et al. (2008).

Figure 2 shows plots of the static drained uniaxial compressional modulus ($M_{\text{drain}}$) as obtained from mechanical loading (black rectangular); the dynamic undrained uniaxial compressional modulus ($M_{\text{sat}}$) as calculated from $V_p$ and $\rho_b$ (green triangular); and the dry uniaxial compressional modulus ($M_{\text{dry}}$) as estimated according to equation (2) (red dots). An estimate for the mineral modulus ($M_{\text{grain}}$) was found within the range of 120–140 GPa based on Chen & Evans (2006). The present results show that $M_{\text{sat}}$ is significantly higher than $M_{\text{drain}}$. Both of them increase with stress. There is no large difference between the $M_{\text{drain}}$ and $M_{\text{dry}}$. However the $M_{\text{dry}}$ is higher than the $M_{\text{drain}}$. The reason for this difference is probably that $M_{\text{drain}}$ accounts for additional plastic deformation.
Figure 1. Stress–strain curves produced during uniaxial deformation. Open circles on the loading curves indicate the mid point of the part of the curve used for obtaining the $M_{\text{drain}}$. The closed and open rectangles indicate stress levels at which the elastic wave velocities were measured during loading and unloading, respectively.

Conclusions

Elastic deformation properties of naturally water saturated Palaeogene clays were determined by using elastic wave velocity measured during triaxial testing under drained conditions. The studied Palaeogene clay is rich in smectite and the smectite content controls the physical properties of the studied clay. When the uniaxial mineral modulus is predicted from grain density, then the drained purely elastic modulus ($M_{\text{dry}}$) can be predicted by Gassmann fluid substitution. $M_{\text{dry}}$ is higher than, but close to, the geotechnically obtained drained uniaxial compressional modulus ($M_{\text{drain}}$). The obtained results can aid in the estimation of geotechnical drained elastic modulus from bulk density and elastic wave velocity. Our results may have implications in engineering practice, including structural design and slope stability analysis. The obtained results indicate that the solid frame of the studied Palaeogene clay behaves elastically.

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Figure 2. Stress–strain curves produced during uniaxial deformation. Open circles on the loading curves indicate the mid point of the part of the curve used for obtaining the Mdrain. The closed and open rectangles indicate stress levels at which the elastic wave velocities were measured during loading and unloading.

References