Estimating the Small Strain Modulus G_0 from DMT tests for loess subsoil as an example of the practical application of the non-seismic method

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ABSTRACT

Seismic tests in geotechnics are used to determine the maximum shear modulus, which is a parameter characterising the subsoil in the range of very small strains. Maximum shear modulus is employed in deformation analyses, in particular when using advanced constitutive models describing the behaviour of the subsoil. Deriving parameters indirectly is a routine procedure in geotechnics. In the absence of seismic measurements or at an early stage of analysis, knowing the correlation between the shear modulus and other parameters measured in situ makes it possible to approximately estimate these parameters. The value of the shear modulus is closely related to, among others, the density of the medium and the shear wave velocity, which is significantly influenced by the in situ vertical effective stress. Therefore, the rule is that the shear modulus increases with depth.

The article presents the results of research on loess subsoil. Based on the seismic dilatometer tests (SDMT), a formula was established that allows the shear modulus to be estimated from non-seismic dilatometer tests (DMT). The results were compared to those obtained in laboratory tests such as bender element test (BET) in an advanced triaxial testing apparatus. Formulas were derived to estimate the maximum shear modulus in the loess subsoil based on the vertical geostatic stress and the value of the constrained modulus M_{DMT}. Moreover, the results were analysed with reference to the results for other soils in Poland and validated in additional field tests.

Keywords: DMT; loess, shear modulus, small strain.

1. Introduction

The highest level of accuracy in determining geotechnical parameters is achieved through direct measurements. Although the values determined in this way are the most valuable, the standard procedure in geotechnics is to derive parameters by correlation, mainly due to time and costs.

Subsoil behaviour is highly non-linear and dependent on many factors. Obtaining a full deformation profile of the subsoil requires time-consuming and expensive laboratory tests, which in many cases require using several methods; for example, Triaxial Test (TRX) with on-sample transducers, combined with Bender Element Test (BET). Therefore, for engineering purposes, a simplified description of deformability is very often used, and the parameters are derived by correlation. In situ tests providing a large amount of data are particularly useful, and one of the most important design parameters is the small strain modulus G_0, which can be determined in seismic measurements based on the shear wave velocity V_s (Hryciw 1990, Dysli and Steiner 2011).

Determination of V_s and G_0 values from non-seismic in situ tests is widely used in engineering but requires calibration for specific ground conditions (Amoroso 2014, Młynarek et al. 2013, Lechowicz et al. 2014, Ivandic et al. 2018). With well-calibrated formulas, the error resulting from approximations is acceptable. In particular, this applies to analyses of smaller buildings or early stages of construction, e.g. concept of the building or assessment of the suitability of the site for the purposes of the spatial development plan (Godlewski 2019). Hence the significance of regional experiences, which permit deriving correlations that enable the use of field tests for rapid assessment of soil parameters (Godlewski 2018).

The current paper presents the possibilities of deriving small strain modulus G_0 from non-seismic DMT measurements for loess soils. The demonstrated results refer to the soils from the Nałęczowski Plateau in the Lublin region. The behaviour of loess from other regions of Poland and the world may be the same, but it may also be regionally specific, because the behaviour of loess formed in different periods, regions and with the participation of various phenomena may differ significantly.

2. DMT and SDMT tests

Marchetti flat dilatometer is a device dedicated to determining soil deformation parameters. It consists of a flat steel blade with a circular flexible membrane and a control and a measurement unit for applying and measuring pressure. It is one of the best tools for testing soil deformability, and the specificity of performing measurement itself makes a strong case in its favour (Marchetti, 1980). Expanding the steel membrane in the soil is a test with controlled displacement, that is, measuring the pressure at the desired (expected) displacement. This makes it possible to estimate the deformability modulus directly in the ground (in situ), which can be the basis for determining the displacements of the designed structure.

The DMT testing procedure is described in the standard EN ISO 22476-11:2017. The interpretation of dilatometric tests is based on three fundamental indicators: material index I_D, horizontal stress K_D and dilatometer modulus E_D, which are determined from the following formulas:

$$I_D = \frac{(p_1 - p_0)}{(p_0 - u_0)}, \quad (1)$$

$$K_D = \frac{(p_0 - u_0)}{\sigma'_{V0}}, \quad (2)$$

$$E_D = 34{,}7(p_1 - p_0), \quad (3)$$

where:
p_0 – lift-off pressure,
p_1 – pressure for 1.1 mm membrane deflection,
u_0 – in-situ equilibrium pore water pressure,
σ'_{v0} – effective stress in situ.

The material index I_D is mainly used to determine the type of soil and its behaviour. The value of the index rises as the content of fractions with larger grain sizes increases. As a broad generalization, it can be assumed that the boundary between silty (fine-grained) and sandy (coarse-grained) soils is I_D=1.8. Like the friction coefficient R_f from CPTU tests, material index I_D determines soil behaviour type (SBT) rather than classifying it based on grain size (Robertson, 2015).

The K_D horizontal stress index reflects the load history of the subsoil and is used, among other things, to determine the OCR overconsolidation ratio. The K_D value for normally consolidated soil (NC) is approximately 2, and for overconsolidated soils (OC), it increases with the degree of preconsolidation. Sometimes, lightly overconsolidated soils (LOC, OCR=1,3-4, Kulhawy et. al. 2003) are also distinguished.

The E_D dilatometric modulus determines the relationship between the stress acting on the membrane and its displacement. However, this modulus is not used for calculating settlement directly, but only reflects the stiffness of the ground and can be used for calculations after taking into account the horizontal stress history, described by the K_D index. The dilatometric constrained modulus M_{DMT} calculated from the original formula (Marchetti 1980) is used to calculate settlements.

Each of these basic indices is relevant to the interpretations described in the present article.

The standard dilatometric set can be additionally equipped with a seismic module to measure shear wave velocity, which allows for performing SDMT tests. The seismic module is located in the rod directly behind the DMT blade and consists of two geophones, separated by 0.5 m, which are receivers for measuring the shear wave generated during the test (Figure 1).

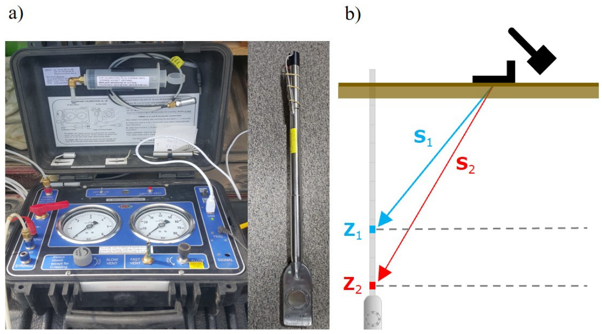

Figure 1. Seismic dilatometer (a) Equipment used in the research (b) SDMT test layout (based on Marchetti et al. 2008)

The measurement of the wave speed is performed using the Frequent-Interval method, usually at depth intervals of 0.5 m or 1.0 m. Figure 2 shows an example of a typical seismogram obtained in loess. SDMT and SCPTU seismic penetration testing procedures are identical to those used in downhole testing, and are gaining popularity as a faster and cheaper alternative to seismic hole testing.

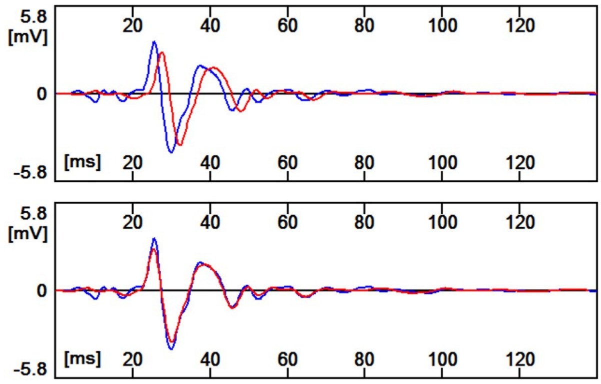

Figure 2. Sample seismograms obtained by SDMT in loess subsoil. Recorded (top) and re-phased (bottom) signal at the depth of 5.0 m in SDMT-2 at the Elizówka site.

Another advantage of SDMT seismic tests is the standard two-sensor measurement called true-interval measurement, which makes it possible to avoid interpretation errors as compared to single-sensor measurements. A wave caused by a single impact is recorded using geophones located at two levels. This makes it easier to interpret the results because the same wave (the same force and start of the recording time) is compared, but recorded at two levels.

The basis for determining the initial (maximum) small strain shear modulus G_0 is the correlation:

$$G_0 = \rho V_s^2 \quad (4)$$

where ρ is the bulk density of the medium.

3. Loess subsoil

The subject of research and analysis is the loess subsoil in the Lublin region. Loess soils are found all over the world. Significant covers are located middle Asia (mainly China), the USA, Argentina, and Eastern Europe. In Poland, they occupy about 7% of the area of the country (Kaczyński 2017). The major role in the process of creating loess covers was played by the wind. These soils are considered specific and due to their macroporosity, they are mainly associated with the phenomenon of collapsibility. However, an important issue is also the large variation in the loess subsoil stiffness, accompanied, significantly, by relative macroscopic homogeneity.

A very good method for identifying the stiffness of loess is in situ testing. The most valuable analyses include static CPTU sounding that provides quasi-continuous data and DMT tests that determine the deformability under natural stress conditions. Combining these tests with seismic measurements, for example SDMT or SCPTU, leads to obtaining a large set of parameters.

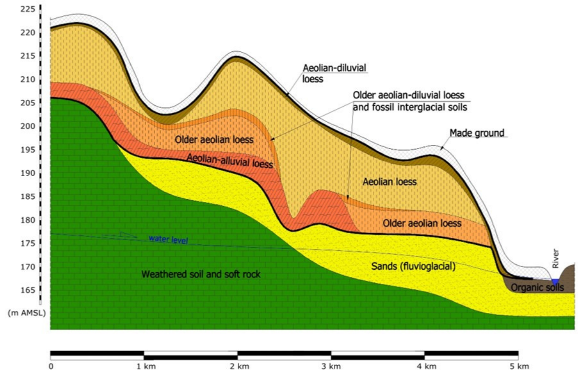

Figure 3. Schematic structure of the loess cover in the Lublin region based on (Nepelski 2021; Maruszczak 2000)

A typical structure of the loess subsoil in Lublin is presented in Figure 3. In the area of Lublin, three main facies of loess should be distinguished: aeolian (typical loess), aeolian-diluvial, and aeolian-alluvial (Nepelski 2021).

The upper, subsurface layer, on average about 1-2 m in depth, consists of aeolian-diluvial loess (silts, clayey silts). These are soils that were originally accumulated by the wind in the form of typical loess soils and then redeposited.

The main subsoil is formed by typical loess soils from the aeolian facies (silts). Their average thickness is about 10 m, but sometimes reaches over 20 m. In some parts of Lublin, older eolic loess soils can also be distinguished in deeper parts of the subsoil; these have an increased content of the sandy fraction (silts, sandy silts).

The deepest layer, below typical loess, consists of loess soils included in the aeolian-alluvial group (clayey silts, silty clay, silts with thin sandy layers), which are deposited directly on residual soil and bedrock or fluvioglacial sands. This facies is much more heterogeneous and variable, which is also visible in parameters measured during in situ tests.

Typical younger loess soils are of key importance for the foundation of building structures. This facies has the largest extent in the loess cover and it is on it that buildings are most commonly founded, which is why analyses focus mainly on these soils. Typical older loess soils occur deeper, are more "sandy" and much stiffer, and have a higher q_c and M_{DMT}. Diluvial and alluvial loess soils are characterized by q_c and M_{DMT} with similar values, but their behaviour is different. Alluvial facies is much deeper than the diluvial, which makes K_D much lower and G_0 higher (Nepelski and Rudko 2021, Nepelski and Lal 2021). It should also be noted that most of the loess cover, in particular typical silty loess soils, exist in an unsaturated state.

Loess soils are mainly silty deposits, which are transitional soils on the border between fine- and coarse-grained. This is reflected in the SBT parameters obtained during tests. Despite its clay fraction content of around 5-10%, the most common behaviour of these soils is the same as that of sandy soils. "Sandy" behaviour is indicated, for example, by SBT nomograms for CPT tests (low R_f and high q_c), and by the material index I_D from the DMT test (I_D>1.8).

4. Tests

The analysis was performed on the basis of the results of reference SDMT tests performed in Lublin in the locations shown in Figure 4. On one of the sites, undisturb samples were also collected for laboratory testing.

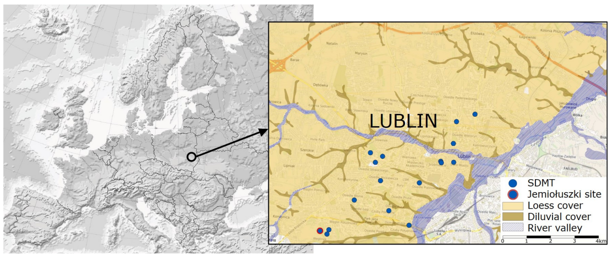

Figure 4. Location of the study sites with marked range of loess cover in the Lublin area

4.1. Field tests

16 SDMT tests were used to determine the G_0 interpretation formulas. The tests were carried out to a depth of 4,0÷20,5 m below ground level; a total of 170 m of soil profile were analysed. Selected representative results are shown in Figures 5-7. Seismic measurements were performed at intervals of 0.5 m or 1.0 m, most often with the exclusion of the subsurface layer.

Loess profiles are characterized by an increased K_D value in the subsurface layer, i.e. up to about 3÷5 m below ground level. Higher K_D values are interpreted as overconsolidation of the subsoil (OC), but in the case of these soils it is not a result of overload, but rather a quasi-overconsolidation effect resulting from, among others, calcium carbonate cementation. In the deeper parts of the subsoil K_D~2, which indicates normally consolidated soils (NC). Nepelski and Rudko (2021) assume for loess soils that the soil is NC (or LOC) for K_D<4 and OC for K_D>4.

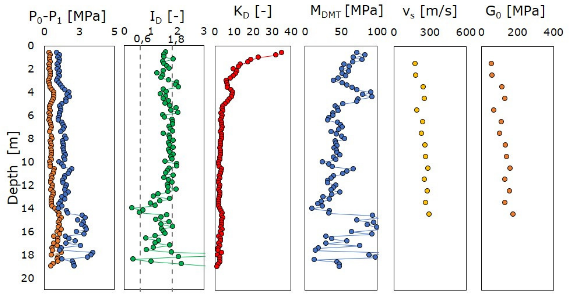

Figure 5. SDMT profiles at the Północna site (SDMT-8)

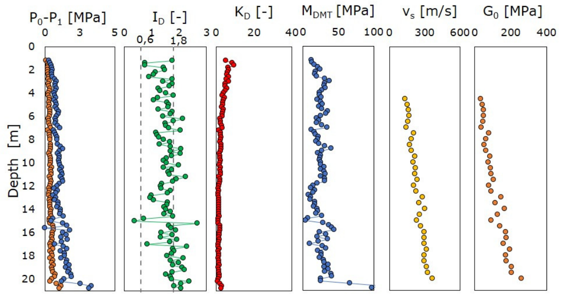

Figure 6. SDMT profiles at the Wieniawska site (SDMT-3)

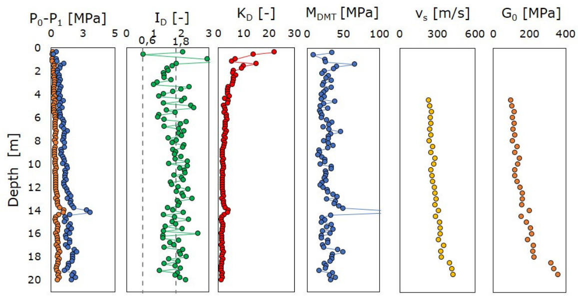

Figure 7. SDMT profiles at the Jasna site (SDMT-3)

The measurements carried out in Lublin show that the constrained modulus M_{DMT} achieves the highest values in the main loess layer, i.e. in typical loess soils. According to Nepelski and Rudko (2021), for NC and LOC Lublin loess soils, the average value of M_{DMT} is 36.6 MPa for the aeolian facies, 6.9 MPa for the aeolian-diluvial facies and 22.8 MPa for the aeolian-alluvial facies. In contrast, for OC loess soils, the average value of M_{DMT} is 62.8 MPa for the aeolian facies, 40.4 MPa for the aeolian-diluvial facies and 36.4 MPa for the aeolian-alluvial facies.

The I_D material indexes in typical loess soils are approx. I_D~1.8, which indicates soils on the border between sandy and silty. However, in diluvial and alluvial layers, where clayey loess soils are present, I_D indices are lower.

The shear wave velocity V_s shows an increasing trend along with depth and ranges from approx. 120 m/s in the zone between 3 and 5 m to approx. 430 m/s at depths of about 20 m. G_0 was determined based on V_s, using formula (4), with a density of 1.9 g/cm^3 assumed as a typical value obtained in laboratory tests for the soils concerned. G_0 values range mainly from 50 to 200 MPa.

4.2. Laboratory tests

During laboratory tests, triaxial compression tests were performed with the measurement of shear wave velocity with the BET method. The tests were carried out on samples with a diameter of 70 mm and a height of 140 mm. The samples were saturated using the back-pressure method prior to the test. The final Skempton B parameter value was a minimum of 0.97.

Tests were carried out on five samples with bender elements installed; on-sample transducers were installed on four of them that were later sheared, while the fifth was used only for seismic testing. The soil samples to be sheared were isotropically consolidated at effective stresses (σ'_3) of 50, 100, 200 and 400 kPa. After isotropic consolidation, samples were sheared under drained condition (TXCID) at a rate of 0.07%/minute (Figure 8). One additional sample was consolidated in several stages to effective stresses of 25, 50, 100, 200, 300, 400, 500, 600, 700, 800, 900, 1000 and 1100 kPa. At each stage of consolidation, seismic wave velocity was measured.

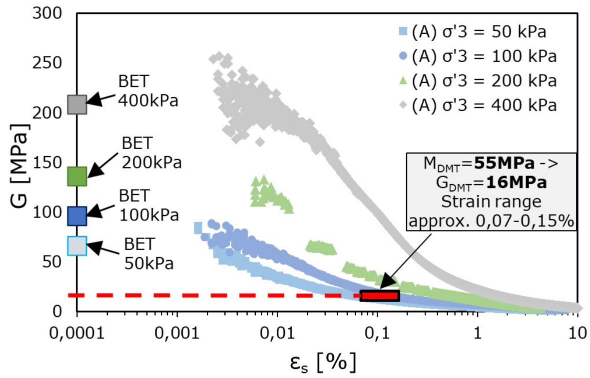

Figure 8. Shear modulus degradation curves from TXCID with BET tests (Jemiołuszki site)

The G_0 determined on the basis of V_s from all measurements for increasing effective stress values is presented in Figure 9 together with a comparison of values for similar soils reported by other researchers (Song et al. 2017, Zhang et al. 2021). Although the values obtained are higher, they fit in with the trend acquired for the soils selected for comparison. It should be highlighted that during the tests, the values of G_0 were obtained at effective stresses of over 1 MPa.

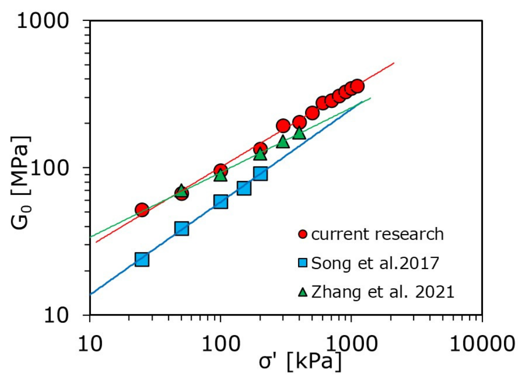

Figure 9. Effect of the mean σ′m effective confining stress on the small strain shear modulus G_0

5. Analysis

The stiffness of the subsoil varies and generally increases with the increase in in situ stresses, as reflected in, among others, soil stiffness degradation curves obtained in triaxial tests (Figure 8) (Clayton 2011). The basic parameter interpreted from DMT studies is the constrained modulus M_{DMT}. In contrast, the maximum shear modulus G_0 determined on the basis of shear wave velocity V_S from seismic measurements describes the initial stiffness, which rises with increasing in situ stresses. DMT measurement, depending on the type of soil, reflects its behaviour in the range of strain between 0.01% and 10% (Amoroso at al. 2013; Marchetti et al. 2008; Mayne 2001). Indicator parameters for loess silts from DMT as well as CPTU studies, i.e. material index I_D and friction coefficient R_f, indicate the behaviour on the border between silty and sandy soils. Thus, according to (Amoroso et al. 2013), it can be assumed in general that M_{DMT} values correspond to a range of strain between about 0.07% and 0.15%. Figure 8 shows this range of strain along with the value of the modulus G_{DMT}=16 MPa, corresponding to the average M_{DMT}=55 MPa in the range of sampling depth for TXCID tests at the Jemiołuszki site. The DMT measurement coincides with TXCID results for 50-100 kPa effective stresses corresponding to geostatic stresses at the sampling depth (z~3.0÷5.0 m b.g.l), which confirms that M_{DMT} values correspond to the assumed deformation range.

5.1. G_0/M_{DMT} and G_{DMT}/G_0 indices

The aim of the analysis was to derive the correlation between the compressibility parameter obtained in the strain range between about 0.07% and 0.15% and the maximum shear modulus recorded at deformation of 0.0001%, taking into account geostatic stresses and the load history of the subsoil. In practice, this is done by determining the indices, e.g. G_0/M_{DMT} or G_{DMT}/G_0, which are usually combined with K_D (Godlewski 2018; Marchetti 2015; Marchetti et al. 2008) or the value of vertical stresses σ_v, which was carried out for the analysed loess soils.

The G_0 values are highly dependent on in situ stresses, so they are smaller for the subsurface layer and increase with depth. Therefore, the highest G_0/M_{DMT} indices were obtained for the aeolian-alluvial group, which ensues from the depth of these soils. This facies occurs at greater depths, often more than 10 meters below the ground level, and thus the subsoil behaviour is in the range of higher in situ stresses, with the value of G_0 higher than for other facies that lie shallower. The lowest values of G_0 were obtained for the aeolian-diluvial facies. Figure 10 shows the determined G_0/M_{DMT} vs. K_D indices for which formulas were derived for specific facies:

$$G_0 = M_{DMT} \cdot 9{,}32 \cdot K_D^{-0{,}98}, \text{ (aeolian)} \quad (5)$$

$$G_0 = M_{DMT} \cdot 22{,}01 \cdot K_D^{-1{,}24}, \text{ (aeolian-alluvial)} \quad (6)$$

$$G_0 = M_{DMT} \cdot 8{,}30 \cdot K_D^{-0{,}82}, \text{ (aeolian-diluvial)} \quad (7)$$

In a generalized approach, the formula takes the following form for all loess soils:

$$G_0 = M_{DMT} \cdot 13{,}68 \cdot K_D^{-1{,}17}, \quad (8)$$

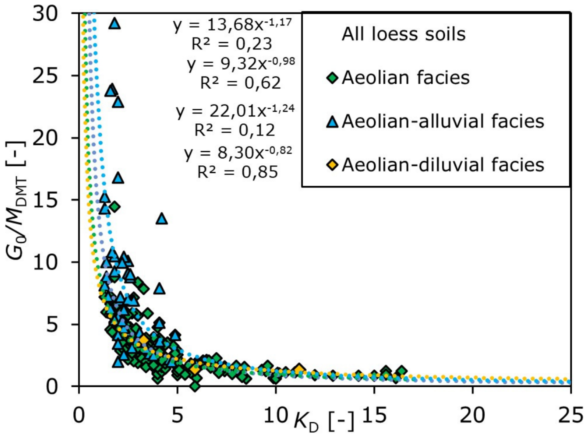

Figure 10. Graph for G_0/M_{DMT} vs. K_D for loess soils divided into facies

In the analyses, indices based on constrained moduli, strain or shear moduli are used interchangeably, so M_{DMT} values were converted to G_{DMT} using the following correlation:

$$G_{DMT} = M_{DMT}\left(\frac{1-2\nu}{2(1-\nu)}\right), \quad (9)$$

assuming that Poisson's ratio ν=0.3. Figure 11 shows G_{DMT}/G_0 vs. K_D indices.

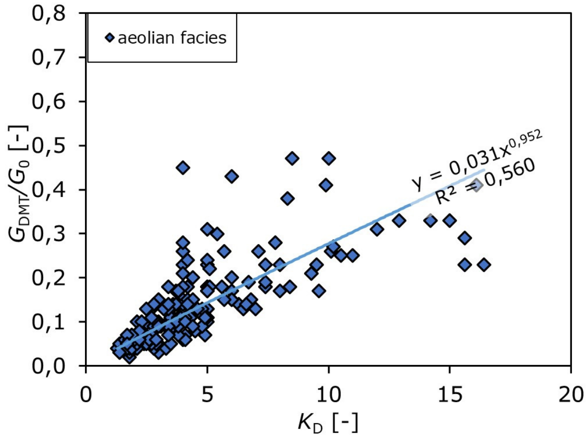

Figure 11. Graph for G_{DMT}/G_0 vs. K_D for (aeolian) loess soils

Figure 12 shows the upward trend in the initial stiffness of the loess subsoil depending on the in situ stresses. After the initial analysis, the results were filtered by rejecting values differing by +-30% from the trend line (Amoroso 2014); subsequently, the trend was determined from the remaining results. The graph was supplemented with data from laboratory BET measurements from the Jemiołuszki site. The following correlations were obtained:

$$G_0=17.72*\sigma_v^{0.40} \text{ for SDMT} \quad (10)$$

$$G_0=8.31*\sigma'^{0.54}_3 \text{ for BET} \quad (11)$$

$$G_0=14.29*\sigma^{*0.44} \text{ for SDMT+BET} \quad (12)$$

σ* referes to σ_v for SDMT and σ'_3 for BET

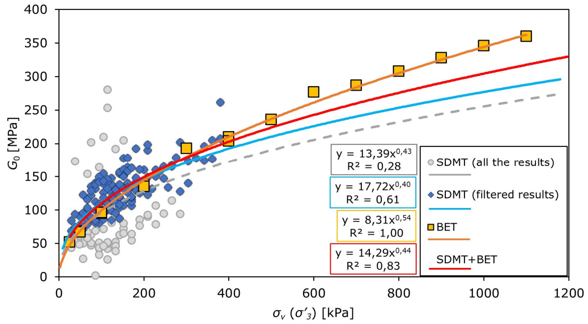

Figure 12. Dependence of G_0 shear modulus on stress (σ_v for SDMT and σ'_3 for BET) for loess soils.

Subsequently, the recorded values of G_{DMT}/G_0 indices were compared depending on in situ stresses. The graph was supplemented with laboratory data, assuming G_0 from the BET measurement and G_{DMT}=16 MPa corresponding to M_{DMT}=55 MPa from the sampling depth. Finally, the distribution shown in Figure 13 was obtained, from which the following correlations were derived:

$$G_0 = \frac{G_{DMT}}{7{,}03\sigma_v^{-0{,}86}} \quad \text{for SDMT} \qquad (13)$$

$$G_0 = \frac{G_{DMT}}{1{,}86\sigma'_3{}^{-0{,}54}} \quad \text{for BET} \qquad (14)$$

$$G_0 = \frac{G_{DMT}}{3{,}61\sigma^{*-0{,}72}} \quad \text{for SDMT+BET} \qquad (15)$$

σ* referes to σ_v for SDMT and σ'_3 for BET

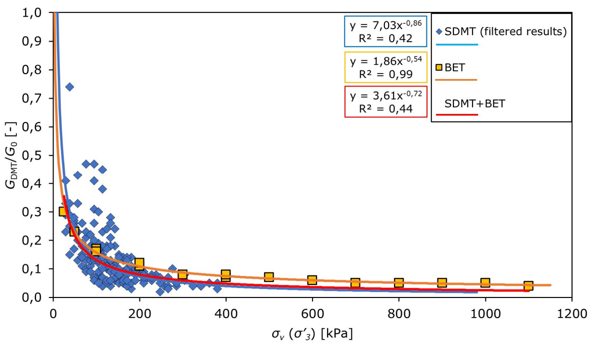

Figure 13. G_{DMT}/G_0 dependence on stress (σ_v for SDMT and σ'_3 for BET) for loess soils.

According to the authors, the fact that laboratory and field results are not an exact match may ensue from the fact that there were less BET data, lack of SDMT measurements for higher stress values i.e. depth over 20 m, and the fact that field measurements (SDMT) were performed on unsaturated soils, and laboratory measurements (BET) on saturated samples. However, both the obtained correlations and the consistency of field and laboratory measurements should be considered satisfactory.

5.2. Results against other soils

The results were compared to the results obtained for other soils and by other researchers. Figure 14 shows the correlation G_{DMT}/G_0 vs. K_D compared to other Polish soils (Godlewski 2016, 2018). The results reflect the trends between those for clays (OC and NC) and for alluvial sands (NC), which can be considered appropriate from the point of view of granulometry.

Figure 15 shows G_0/M_{DMT} vs. K_D against reference correlations (Marchetti et al. 2008) with respect to which the determined results for loess should be considered to be in line with the trend for soils on the border between sandy and silty.

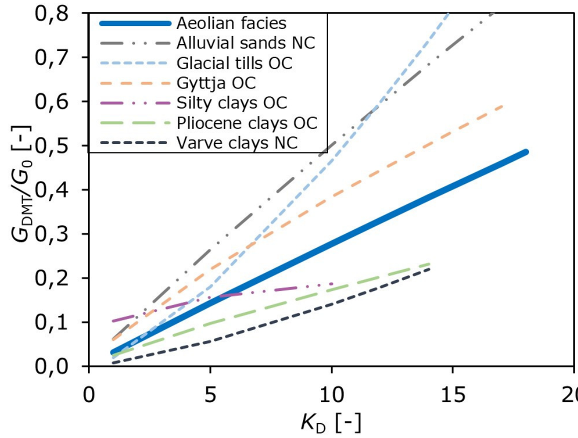

Figure 14. Graph of G_{DMT}/G_0 vs. K_D index for loess soils against other Polish soils.

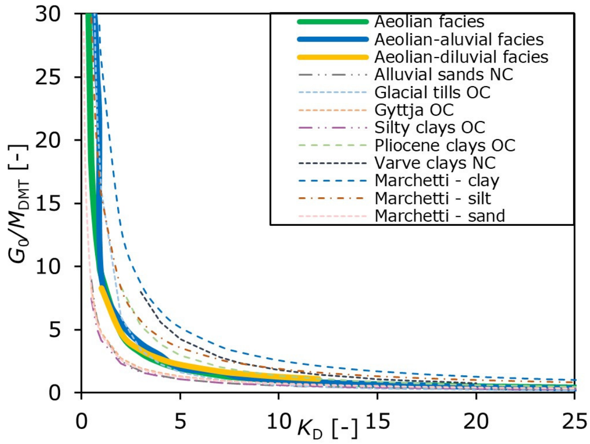

Figure 15. Graph of G_0/M_{DMT} vs. K_D index for loess soils against Marchetti's primary relations.

5.3. Validation of formulas

Comparison of values derived from formulas with actual measurements allows researchers to test the reliability of determined formulas. For selected studies, the G_0 graphs derived from SDMT tests were plotted with values determined using formulas (5÷8), (10), (13). The analysis included both the testing sites used to derive the formulas (Figure 16 a÷c), as well as the results from tests performed after the derivation of the correlations (Figure 16d).

In each of the graphs, there is a noticeable trend where the value of G_0 increases along with depth, largely coinciding with the general trend line derived from Eq. (10), which is based on in situ stresses. However, in some cases, e.g. for the Wieniawska site (Figure 16b), there is a significant discrepancy in the depth range between 5 m and 15 m, so this formula can only be used for preliminary estimation of expected G_0 values, e.g. at the stage before testing.

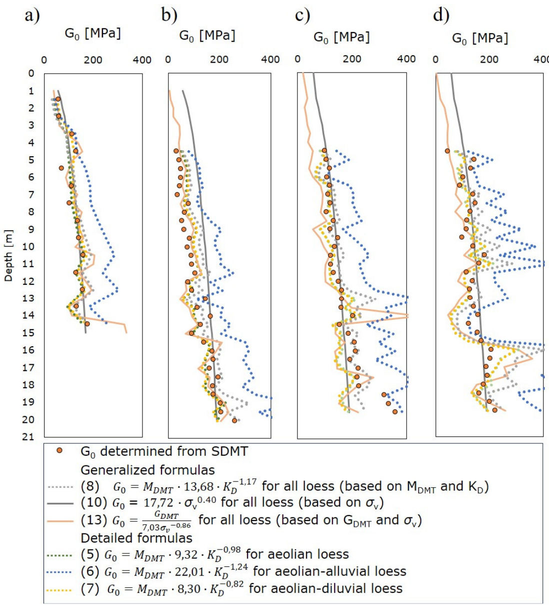

Figure 16. Comparison of G_0 determined from SDMT and predicted from DMT data at sites: a) Północna (SDMT-8), b) Wieniawska (SMDT-3), c) Jasna (SMDT-3), d) Chodźki (SDMT-5).

In general, the best fit is obtained for Eq. (8) and Eq. (13), which take into account the results of all measurements, regardless of the facies. On the other hand, detailed formulas derived for specific facies according to Eq. (5÷7) are less useful in global terms, but allow for better matching of results locally, within soils that are genetically compatible with the intended purpose of the formula. The possibility of their implementation requires a deeper analysis of the subsoil structure, so they will be applicable in detailed analyses.

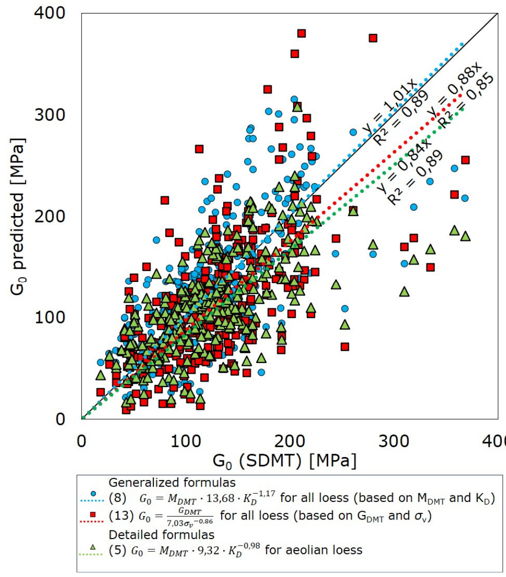

Figure 17. Comparison between G_0 (SDMT) vs. G_0 predicted for the three main formulas.

For Eq. (5), Eq. (8) and Eq. (13) a summary of measured vs. predicted values was made for all test sites included in the analysis, as shown in Figure 17. For each result group, trend lines with a forced intercept of (0, 0) were determined. The best fit was obtained for Eq. (8), with a coefficient of determination R^2=0.89, which almost overlapped with the line of perfect fit. The fit of the other two formulas was not as good, in general indicating that the G_0 modulus was lowered by about 10÷15%, which is acceptable from the engineering point of view and appropriate in terms of safety. Both the degree of fit and the determination coefficients obtained for these three formulas are considered very good.

6. Conclusions

The demonstrated correlations for loess soils can form the basis for the determination of the small strain modulus G_0 using solely the results from non-seismic DMT tests. This is particularly important in situations where seismic measurements are not available or the conditions for performing them are unfavourable (e.g. urban area, interference effects, etc.). In addition, at the preliminary stage, before testing, the G_0 value can be estimated from Eq. (10) based on in situ stresses. On the other hand, when DMT results are available, the use of Eq. (8) is suggested in general cases, and in more detailed analyses - Eq. (5÷7) depending on the specific facies.

In addition, using reference curves developed for a given soil type makes it possible to estimate the full variability of stiffness. This is possible because, as experiences of other researchers suggest (Monaco et al. 2009), the value of the G_{DMT}/G_0 index determined from in situ tests serves as the ordinate for the normalized graph of G-σ. On this basis, it is possible to approximate the distribution of elasticity parameter variation across the whole range of analysed deformations using the proposed auxiliary curve and relying on data from one test method, in this case - DMT.

Acknowledgements

The research leading to these results has received funding from the commissioned task entitled "VIA CARPATIA Universities of Technology Network named after the President of the Republic of Poland Lech Kaczyński" contract no. MEiN/2022/DPI/2575, MEiN/2022/DPI/2577, MEiN/2022/DPI/2578 action entitled "ISKRA – building inter-university research teams.

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