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Research paper

Use of DMT and CPTU tests in the evaluation of shear modulus G_0 for soils of different origin

Zbigniew Młynarek[1], Jędrzej Wierzbicki[2], Paola Monaco[3], Katarzyna Stefaniak[4]

Abstract: The subject of this article is the analysis of the relationship between G_0/M_{DMT} and K_D, where G_0 is the small strain shear modulus, while M_{DMT} and K_D are respectively the constrained modulus and the horizontal stress index determined from DMT tests. This relationship allows to determine a profile with depth of G_0 from standard DMT test results, useful when data from non-seismic DMT investigations are available. The analysis was based on a large amount of data for a wide range of soils of different origins in Poland. The dataset included OC and NC loams, silts, medium sands, silty sands and fine sands. The overconsolidation ratio (OCR) was estimated using data from CPTU and DMT tests. The obtained empirical G_0/M_{DMT} vs. K_D relationships were compared with the correlations established by Marchetti et al. [1] for different soil types. To account for the significant influence of overconsolidation, an original empirical relationship between G_0/σ'_p and K_D, where σ'_p is the preconsolidation stress, was defined based on data from all investigated fine-grained soils.

Keywords: CPTU, DMT, initial shear modulus, various soils

[1]Prof., DSc., PhD., Eng., University of Life Sciences, Poznań, Poland, e-mail: zbigniew.mlynarek@gmail.com, ORCID: 0000-0002-6156-4286
[2]Assoc. Prof., DSc., PhD., Eng., Institute of Geology, Adam Mickiewicz University, Poznań, Poland, e-mail: jwi@amu.edu.pl, ORCID: 0000-0003-1447-623X
[3]Prof., DSc., PhD., Eng., University of L'Aquila, L'Aquila, Italy, e-mail: paola.monaco@univaq.it, ORCID: 0000-0002-1473-158X
[4]PhD., Eng., Institute of Geology, Adam Mickiewicz University, Poznań, Poland, e-mail: stefaniak@amu.edu.pl, ORCID: 0000-0003-4016-407X

1. Introduction

The achievements of the last dozen or so years in the field of subsoil research in in-situ conditions allow to determine a wide range of geotechnical parameters of soils, which are necessary for the preparation of a geotechnical design for the planned investment. The CPTU and DMT tests take up a special position in these studies. In the group of geotechnical parameters, which are essential to design the installation of many engineering structures, there are parameters that define strain of the subsoil, e.g. shear modulus G_0, constrained modulus M_0 or Young modulus E_0. The CPTU and DMT methods mentioned above are particularly convenient for determining the profile of changes of these moduli in the subsoil. To determine the shear modulus G_0 in the profile, a special seismic SCPTU or SDMT survey technique is used. The cost of these studies, however, is relatively high, hence the concept of using the empirical correlation between the G_0 modulus and the parameters of a standard DMT to evaluate the modulus [1]. One should be aware that there are many independent variables that affect the quality of the evaluation of the G_0 modulus if this correlation is to be applied. It is generally accepted that the quality of the sought-after geotechnical parameter in the subsoil is determined by two factors. The first is related to the quality of the testing technique, e.g. SCPTU, SDMT or DMT [2, 3], and the second one to the parameter variability, which is related to the properties of the soil found in the subsoil [4].

This paper analyzes the influence of the latter group of factors on the correlation between the G_0 modulus and the K_D index from DMT with particular emphasis on the subsoil preconsolidation effect.

2. Location and geological characteristics of tests sites

The research was carried out in five locations in Poland, four in the area covered by the Late Pleistocene glaciation and one in the impact zone of periglacial processes in the Pleistocene (Fig. 1). Two research sites, Kaźmierz and Lipno, are located within the Weichsel glaciation, which ended about 15.000 years ago. The geological formations of the near-surface area are dominated by a layer of loam and glacial sands over a dozen meters thick. In the several-meter-long subsurface zone, loams come mainly from melt-out facies and, therefore, they are characterized by a low degree of pre-consolidation. They rest on loams of the lodgement facies with a clearly higher degree of preconsolidation (Kaźmierz research site). The clay fraction content in glacial clays does not exceed 25%. They are dominated by the sand fraction, even up to 70%. The research sites of Jarocin and Koźmin are located in the Riss glaciation zone, in the foreground of the Weichsel glaciation line. Glacial sediments are found here as well, however, the dominant soil in the profile is loam of the lodgement facies, they are consolidated. A characteristic feature of these loams is a high content of calcium carbonate, above 10%, a reduced content of the sand fraction in relation to the loams of the Weichsel glaciation, with a simultaneous increase in the content of the silt fraction (up to 40%). These clays also have a characteristic gray-brown

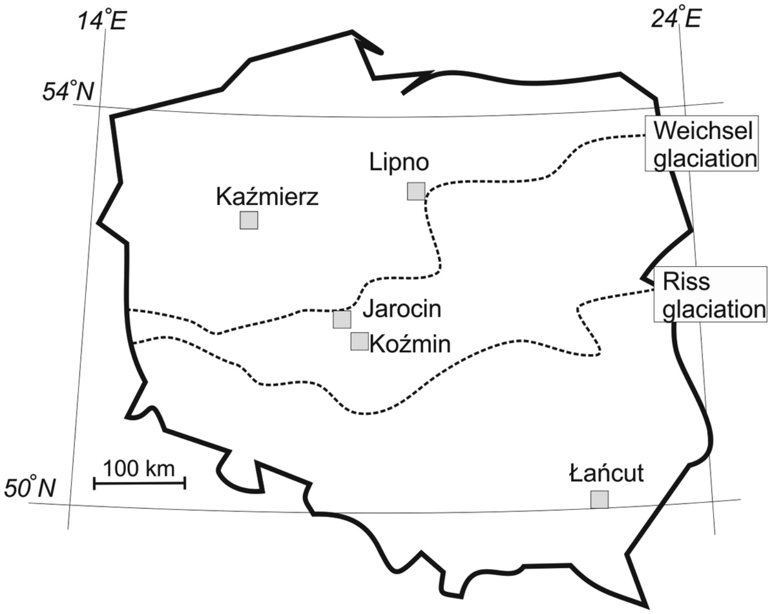

Fig. 1. Location of test sites on the contour of Poland

color and are often called gray loams. They are considered to be a very good building subsoil. A geologically separate research site is Łańcut, located in the zone of loess covers and loess-like silts. These soils were created in the Middle and Younger Pleistocene as extensive covers of aeolian silty sediments, deposited in the foreland of the Pleistocene ice sheet. The particle size distribution of the tested silts is very homogeneous and is characterized by the presence of 60 to 70% of the silt fraction and about 20% of the sand fraction. the frequent occurrence of carbonate cementation, which causes the effect of quasipreconsolidation, in the subsurface zone, is a characteristic element of the examined loess covers [5].

3. Evaluation of preconsolidation for the examined subsoil based on CPTU and DMT

The variability of soil mechanical parameters, including strain and shear modules, identified by CPTU and DMT tests is according to Powell, related to [6]:

– the geological regime,
– the hydrological regime,
– the engineering regime.

The geological regime is defined by soil origin and geological processes and it determines the nature and structure of the subsoil. These issues for the analyzed research sites are presented in part 2. The hydrological regime is of significant importance for the changes in the consistency of the cohesive soils of the subsoil. Seasonal changes in the groundwater level, which are determined by precipitation in the annual cycle, can cause very significant local changes in the state of consistency, even from hard-plastic to soft-plastic state. The consequence of these changes, as well as of the pre-consolidation effect, often means significant differences in shear strength parameters, and above all, deformation moduli, including the G_0 modulus. Such a situation occurs in moraine clay in the territory of Poland. A characteristic element in the structure of these sediments are sands and sand veins of varying thickness. Through these forms, rainwater easily infiltrates the subsoil and supports the moraine clay top layer. The analyzed research sites were located outside the built-up area, hence the effect of the engineering regime did not have to be taken into account in the assessment of the degree of pre-consolidation of the subsoil. The degree of pre-consolidation of the subsoil is usually determined on the basis of the OCR pre-consolidation coefficient or the pre-consolidation stress σ'_p [7, 8]. It is possible to obtain a continuous profile of changes of these parameters in the subsoil from CPTU and DMT tests. The use of the OCR coefficient determined from the CPTU and DMT tests allowed a more objective evaluation of this coefficient, as well as the evaluation of the impact of the inhomogeneity of the subsoil structure on the recorded parameters of the CPTU and DMT tests, used to determine the value of the OCR.

Based on the CPTU test, the OCR can be calculated from the correlation [7]

$$\text{OCR}_{\text{CPTU}} = 5,68 \ln Q_t - 15.64 \tag{3.1}$$

where: Q_t – normalized cone resistance.

The original Marchetti formula [9] was used to calculate the OCR from the DMT test

$$\text{OCR}_{\text{DMT}} = (0.5K_D)^{1.56} \tag{3.2}$$

$$K_D = \frac{(p_0 - u_0)}{\sigma'_{v0}} \tag{3.3}$$

where: p_0 – corrected first reading of DMT pressure, u_0 – hydrostatic pore pressure, σ'_{v0} – vertical effective overburden stress.

Measured parameters from CPTU and DMT to calculate the OCR are q_t and p_0.To compare the OCR values from both tests, the comparison of these values should be made at the determined levels of effective vertical stress σ'_{v0} or at a determined depth – z, due to the influence of geostatic stress components on these parameters. The example of the OCR evaluation results related to the CPTU, DMT and borehole data are shown in Fig. 2. The obtained values of the OCR for this subsoil from both studies are very similar (Fig. 3) and the average OCR values that characterize the entire subsoil do not significantly differ from the statistical point of view at the level of $\alpha = 0.05$. To qualify the subsoil as normally consolidated or pre-consolidated, the obtained OCR profiles were used as the base for all analyzed locations. OCR has changed from 1 to 11 for each location.

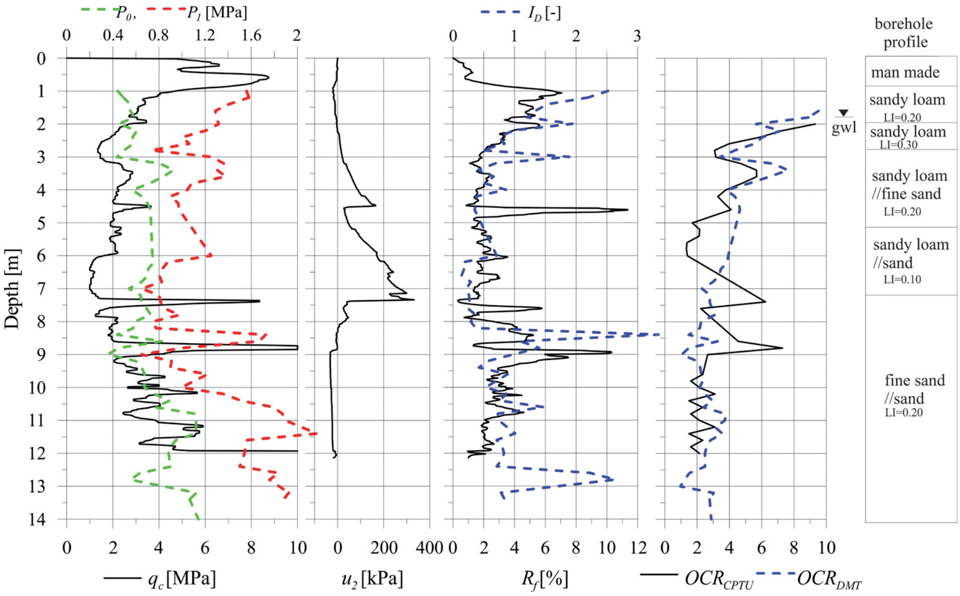

Fig. 2. CPTU, DMT and borehole profile with calculated OCR profile at Lipno test site

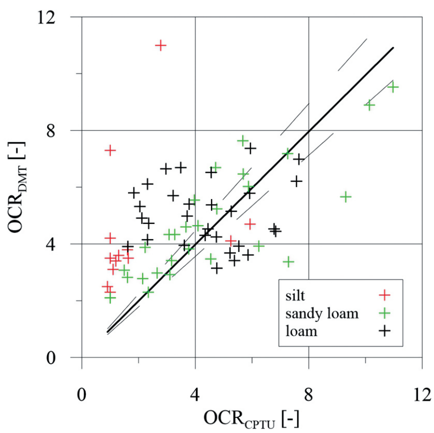

Fig. 3. Comparison of OCR calculated on the basis of CPTU and DMT at Łańcut (silt), Jarocin (loam) and Lipno (sandy loam) test sites with 95% confidence intervals for 1:1 line

A more differentiated assessment of the OCR from both studies was obtained for the loam subsoil in Kazimierz. In the homogeneous zones of the subsoil, the OCR values differed slightly, whereas, in the zone of the subsoil with thin layers of greater or lesser rigidity of, e.g. sand, the assessment of the OCR was significantly different. It is worth to notice, that in the case of low OCR values (NC soils) DMT slightly overestimates the OCR, in contrast to OC soils (Fig. 3). However, the mean values of the OCR for the entire subsoil profile did not significantly differ at the level of $\alpha = 0.05$.

4. Theoretical basis for the evaluation of the correlation between the shear modulus G_0 and DMT parameters

To determine the profile of changes for the shear modulus G_0 in the subsoil, the correlation shown by the Eq. (4.1) is used [1].

$$\frac{G_0}{M_{\text{DMT}}} = f(K_D) \tag{4.1}$$

This correlation is purely empirical and dimensionally heterogeneous [10]. The independent variables in this equation G_0, M_{DMT}, K_D are obtained from two different and independent tests. For modulus G_0, it is a seismic dilatometer test. Constrained modulus M_{DMT} and horizontal stress index – K_D, are calculated based on the measurements of p_1, p_0 in a standard dilatometer test. The equations for these calculations are generally known correlations:

$$G_0 = \rho V_s^2 \tag{4.2}$$

$$M_{\text{DMT}} = R_M E_D \tag{4.3}$$

$$R_M = f(I_D K_D) \tag{4.4}$$

where: V_S – shear wave velocity, ρ – density of the soil, E_D – dilatometer modulus, I_D – material index

$$I_D = \frac{(p_1 - p_0)}{(p_0 - u_0)} \tag{4.5}$$

where: p_1 – corrected second reading.

Identification of the variables that will affect the functional form of the correlation (4.1) can be obtained from the functionals that define the dilatometric test process and the shear modulus G_0, determined from the seismic wave measurement. In the case of shear modulus G_0, Lee and Stokes [11] and Jamiolkowski et al. [12] systematized the factors that influence this modulus in the original notation:

$$G_0 = f(\sigma'_{v0} e_0, \text{OCR}, S_r, C, K, T) \tag{4.6}$$

where: e_0 – initial void ratio, OCR – overconsolidation ratio, S_r – degree of saturation, C – grain characteristics, K – soil structure, T – temperature.

Partial solution of Eq. (4.6) was given by Hardin [13] and Jamiolkowski et al. [12].

The process of dilatometric testing is described by a functional:

$$F_2 = f(P_d, V_d, Q_{d1}, Q_{d2}) \tag{4.7}$$

where: P_d – measured process parameters, e.g. pressure p_0, p_1, V_d – deposition velocity of the dilatometer membrane, Q_{d2} – properties of the membrane.

Parameter Q_{1d} (in the case of mineral soil) is a function of several variables

$$Q_{d1} = f(x_1, \ldots, x_6) \tag{4.8}$$

where: x_1 – effective volumetric weight of the soil, x_2 – water content or plastic limit, x_3 – void ratio or relative density, x_4 – clay, silt and sand fraction content, x_5 – parameter defining soil structure, cementation effect or preconsolidation effect – OCR, x_6 – parameter specifying the components of stress in the subsoil.

The Q_{d2} parameter defines measurement uncertainties related to the quality of the dilatometer and the effect of the operator performing the tests [2, 14]. To ensure the quality and comparability of the DMT tests, it is necessary to complete them with a standard dilatometer by one operator. This type of principle was applied for research in all test sites.

From equations (4.6) and (4.7), some important observations can be made:

– the correlation between the initial shear modulus G_0 and the parameter K_D, presented with equation (4.1), is influenced by a significant number of independent variables. A general solution for this correlation is unknown. Taking into account the variables that may have the most significant impact on the functional form of this relationship, e.g. grain size, overconsolidation ratio, vertical effective overburden stress σ'_{v0}, leads to the determination of the partial functions of this equation
– From a statistical point of view, in order to investigate the influence of one variable from equations (4.5) and (4.6) on the functional form of the correlation (4.1), other variables should be kept constant, e.g. the mean value. When analyzing the impact of variability of the type of soil on the correlation (4.1), one should take into account the impact of the pre-consolidation effect on this correlation, i.e. separately for normally consolidated and pre-consolidated soils.
– equation (4.1) is not written in the dimensional invariant form [10] hence for the variables G_0, M_{DMT} measures, preferably homogeneous e.g. MPa, kPa, must be defined,
– stress σ'_{v0} influences both measured values of K_D and G_0, observation pairs G_0, therefore, K_D at the same level σ'_{v0} must be created for the analysis.

Based on the above conclusions, the concept adopted by Marchetti et al. [1] should be considered as extremely valuable when searching for the form of a function for equation (4.1). In this concept, equations were determined for three main types of soil – clay, silt, sand. The studied soils represented normally consolidated sediments, relatively lightly OC. The correlations obtained by Matchetti et al. [1] were taken as reference for the comparative analysis with the research results.

5. Analysis of results

On the basis of equations (4.6) and (4.7) as well as origin diversity and soil macrostructure, the analysis of the correlation written with equation (4.1) was carried out in the following soil groups:

– clays (above 30% clay fraction),
– sandy loams, loams (10÷30% clay fraction),
– silts (up to 10% clay fraction),

– medium sands,
– silty sands,
– fine sands.

This division corresponds to the national classification according to the Polish Standards and includes soil groups separated by Marchetti et al. [1]. The total number of analyzed tests was 989.

Figure 4 shows the global correlation between the measured moduli $G_{0(m)}$ and the K_D index. This figure confirms entirely the conclusions formulated by Marchetti et al., [1] *i.e.*:
– There is a functional correlation between G_0/M_{DMT} ratio and K_D index.
– Correlation between those variables should be constructed for the specific groups of soils, at least with regard to cohesive and non-cohesive soils.
– These correlations are affected by preconsolidation effect which can be defined by σ'_p stress or OCR.

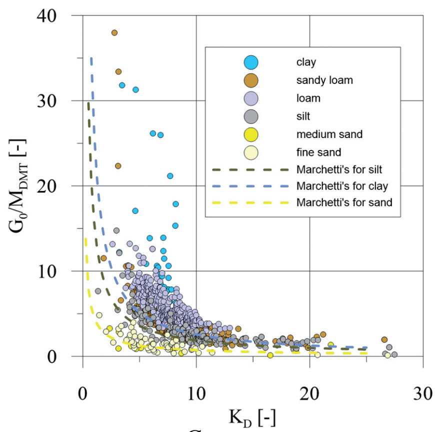

Fig. 4. Relationship between ratio $\dfrac{G_{0(m)}}{M_{\mathrm{DMT}}}$ and K_D index for investigated soils on the background of original Marchetti et al. [1] formulas

These conclusions prove that it is necessary to analyze the relationship between the ratio $G_{(m)}/M_{\mathrm{DMT}}$ and the K_D index in selected groups of soil.

Figures 5 and 6 prove that for a highly preconsolidated clay, measured $G_{0(m)}$ modulus differs significantly from calculated $G_{0(c)}$ modulus, regardless of Marchetti group classification.

An interesting element of the analysis is the fact that the $G_{0(c)}$ and $G_{0(m)}$ moduli are close to the correlation 1–1 line for low values of the measured $G_{0(m)}$. The same effect was found by Młynarek et al. [15] when comparing the constrained modulus from DMT and CPTU tests for overconsolidated Pliocene clays. Marchetti's formula for determining the $G_{0(m)}$ modulus needs to be corrected according to general form (Eq. (5.1)) and parameters values presented in Table 1. The determined empirical relationship is of significant statistical value, at the significance level $\alpha = 0.05$.

$$\frac{G_{0(m)}}{M_{\mathrm{DMT}}} = A(K_D)^B \tag{5.1}$$

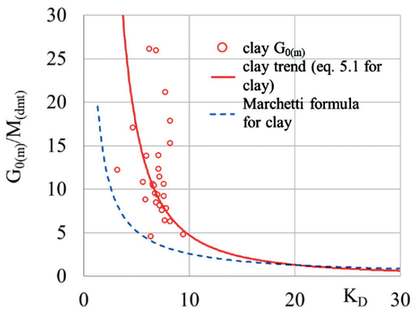

Fig. 5. Relationships between ratio $\frac{G_{0(m)}}{M_{\mathrm{DMT}}}$ and K_D index for clay

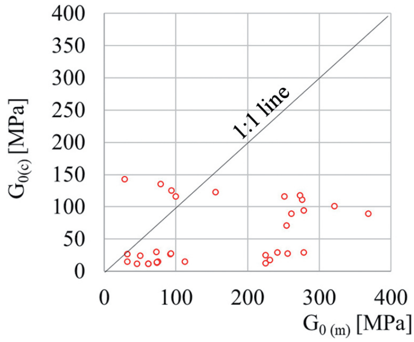

Fig. 6. Relationships between measured shear modulus $G_{0(m)}$ and calculated shear modulus $G_{0(c)}$ after Marchetti equation for clay

Table 1. Parameter values for equation (5.1) and coefficients of determination according to different soil types

Soil type	Parameter values for equation (5.1)		Coefficient of determination
	A [–]	B [–]	R^2
clay	342.75	–1.861	0.6102
sandy loam	48.785	–1.294	0.7341
loam	50.096	–1.114	0.6603
silt	22.608	–0.998	0.7083
sand	8.7499	–1.283	0.7684
fine/silty sand	16.716	–1.184	0.6582

Figures 7 and 8 show the position of the $G_{0(m)}$ modulus relative to the $G_{0(c)}$ modulus for the preconsolidated sandy loam. The calculated values of the $G_{0(c)}$ modulus were determined for the classification of sandy loam as the clay group according to Marchetti – orange lines, and silt – gray lines. This figure proves that the $G_{0(m)}$ and $G_{0(c)}$ moduli for the clay group (according to Marchetti) are more similar and the Marchetti formula can be used to determine $G_{0(m)}$ or that they require a small adjustment. The empirical formula for this correlation is given by the equation (5.1) and Table 1.

The evaluation of this correlation is statistically significant. Once again the same conclusion can be drawn, the low values of the $G_{0(m)}$ and $G_{0(c)}$ moduli lie on the correlation 1–1 line.

Figures 9 and 10 show that the measured shear modulus $G_{0(m)}$ for the pre-consolidated loams is higher than the one calculated according to the Marchetti equation for clay or silt. The application of Marchetti formula for clay is useful for NC – loam. $G_{0(m)}$ measurements for this type of loams are very close to 1–1 line. The corrected equation for determining the G_0 modulus based on the K_D index is according to (5.1) and Table 1. This relationship is statistically significant.

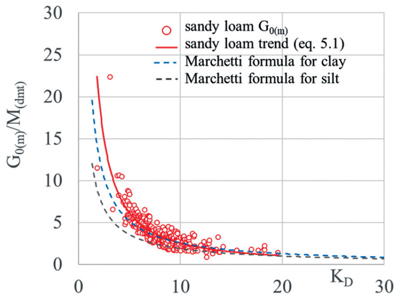

Fig. 7. Relationships between ratio $\frac{G_{0(m)}}{M_{\text{DMT}}}$ and K_D index for sandy loam

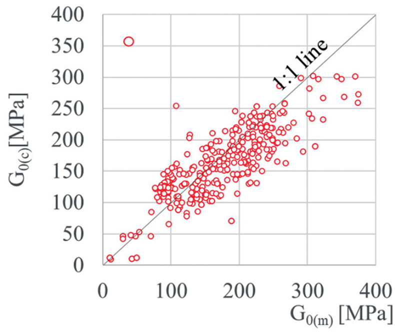

Fig. 8. Relationships between measured shear modulus $G_{0(m)}$ and calculated shear modulus $G_{0(c)}$ after Marchetti equation for sandy loam

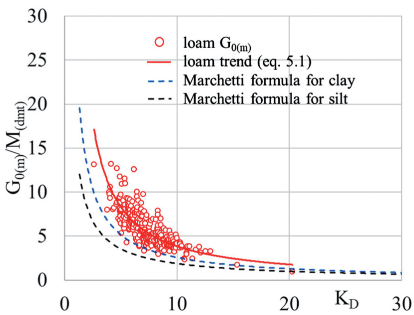

Fig. 9. Relationships between ratio $\frac{G_{0(m)}}{M_{\text{DMT}}}$ and K_D index for loam

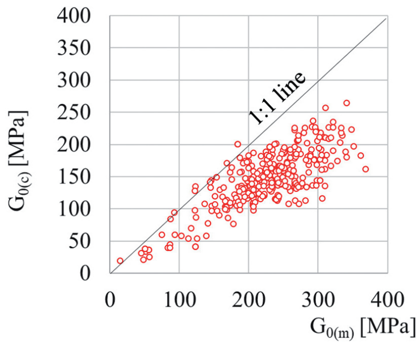

Fig. 10. Relationships between measured shear modulus $G_{0(m)}$ and calculated shear modulus $G_{0(c)}$ after Marchetti equation for loam

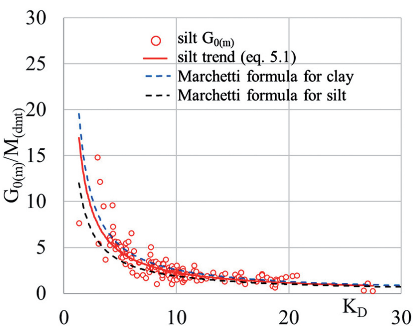

Fig. 11. Relationships between ratio $\frac{G_{0(m)}}{M_{\text{DMT}}}$ and K_D index for silt

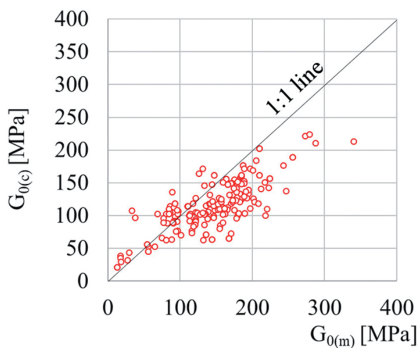

Fig. 12. Relationships between measured shear modulus $G_{0(m)}$ and calculated shear modulus $G_{0(c)}$ after Marchetti equation for silt

The Marchetti equation for clay requires a slight adjustment and, in principle, can be used to predict $G_{0(m)}$ based on K_D for OC and NC silts (Fig. 11 and Fig. 12). The calculated correlation has a high regression coefficient R^2 = 0.708 (Eq. 5.1 and Table 1).

The measured values of $G_{0(m)}$ modulus for fine sands and medium sands are located between the values determined from the Marchetti formula for sands (Fig. 13 and Fig. 14). Generally preconsolidated sands with a more uniform macrostructure are characterized by higher values of $G_{0(m)}$ in the radius compared to $G_{0(c)}$. The Marchetti formula for sand is closer to the determined dependence for the $G_{0(m)}$ value.

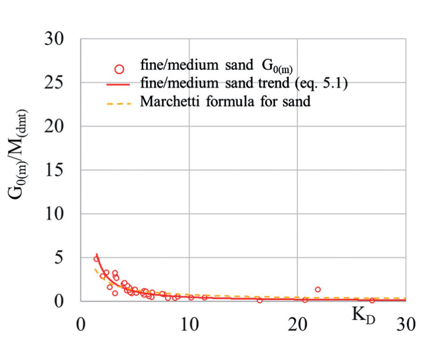

Fig. 13. Relationships between ratio $\frac{G_{0(m)}}{M_{\text{DMT}}}$ and K_D index for fine/medium sand

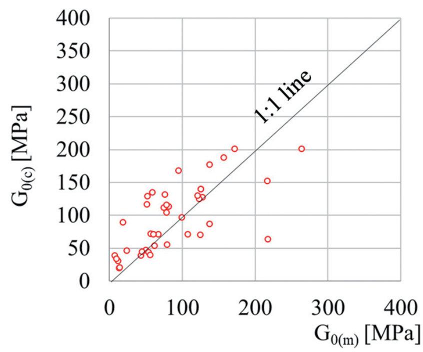

Fig. 14. Relationships between measured shear modulus $G_{0(m)}$ and calculated shear modulus $G_{0(c)}$ after Marchetti equation for sand

Figures 15 and 16 indicates well that the measured values of the $G_{0(m)}$ modulus for fine/silty sands shows a very similar trend of changes with the variable of the K_D index as for how the $G_{0(c)}$ modulus was calculated according to the Marchetti correlation for sands. The value is evenly placed in relation to the 1–1 line (Fig. 15 and Fig. 16). On

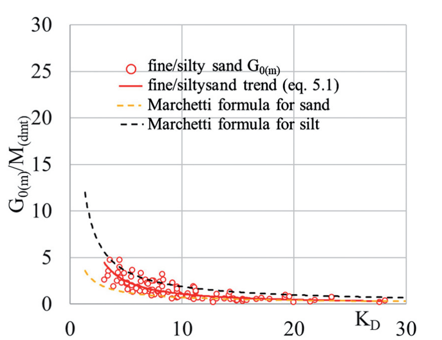

Fig. 15. Relationships between ratio $\frac{G_{0(m)}}{M_{\text{DMT}}}$ and K_D index for fine/silty sand

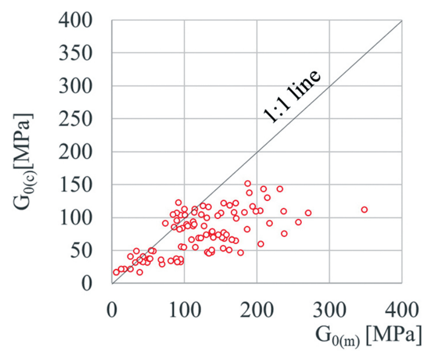

Fig. 16. Relationships between measured shear modulus $G_{0(m)}$ and calculated shear modulus $G_{0(c)}$ after Marchetti equation for sand

their location it can be influence of the preconsolidation effect and the Marchetti equation requires a slight correction. The obtained correlation between $G_{0(m)}/M_{\mathrm{DMT}}$ ratio and the K_D index is as presented in equation (5.1) and Table 1.

Since the preconsolidation effect in cohesive soils on the functional shape of the relationship between the $G_{0(m)}$ modulus and the K_D index, a new correlation was established. In the correlation, the $G_{0(m)}$ shear modulus was normalized by overconsolidation stress σ'_p. The assessment of this relationship is very interesting. Figure 17 shows the location of soils examined to determine the groups of cohesive soils. In this figure, it is possible to delineate two areas A and B that are far away from the approximating function for the dependence $G_{0(m)}/\sigma'_p$ vs. K_D. These areas are to the fissured clays, silt and loams. These soils are subject to separate interpretation. The analysis of this correlation shows that the designated form of the function is of statistical significance and seems to be a valuable element of this study, because it allows to determine the $G_{0(m)}$ modulus based on the K_D index for all cohesive soils.

(5.2) $$\frac{G_{0(m)}}{\sigma'_p} = 2194.9K_D^{-1.178}R^2 = 0.7573$$

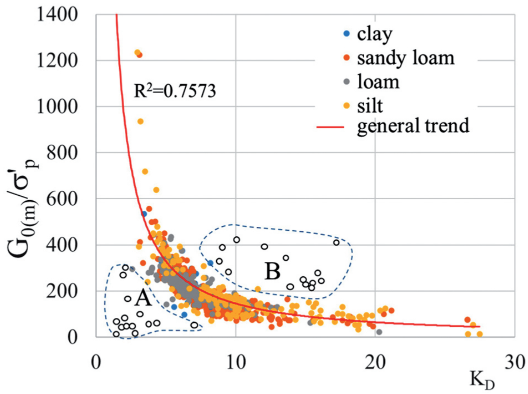

Fig. 17. Relationships between measured shear modulus $G_{0(m)}$ normalized by σ'_p and K_D parameter for clay, sandy loam, loam and silt

6. Summary and conclusions

The obtained research results allow to formulate a few general conclusions:

– In the construction of the correlation between the ratio of shear modulus and preconsolidation stress, and the K_D index, it is necessary to take into account the type of soil in general with a clear division into cohesive and non-cohesive soils. This fully confirms the concept of determining this relationship by Marchetti and partners.
– Significant influence on the functional form of the equation (5.1) equals the preconsolidation effect, hence, the examined preconsolidated loams, clays especially, the Marchetti formulas require some correction.

– A satisfactory agreement between the measured $G_{0(m)}$ modulus and the $G_{0(c)}$ calculated from the Marchetti formulas was obtained for the medium sands/fine sands and NC silts. Marchetti formulas for these soils require a small correction. High compliance of $G_{0(m)}$ and $G_{0(c)}$ moduli found for all soils in the area of low $G_{0(m)}$ values and low K_D values.
– High statistical significance of the equation (5.2) is extremely useful for practical purposes. This relationship allows, using the DMT test, to determine a continuous change in the subsoil of differentiated origin of the G_0 modulus with depth.
– Fissured clays and soils with cementation effect require extensive analysis and interpretation.
– The relationship between $G_{0(m)}/\sigma'_p$ ratio and K_D can be considered very promising in determining the modulus G_0 for the whole set of preconsolidated cohesive soils.

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Wykorzystanie badań DMT i CPTU do oceny modułu ścinania G_0 gruntów o różnej genezie

Słowa kluczowe: CPTU, DMT, początkowa wartość modułu ścinania, różne grunty

Streszczenie:

Przedmiotem artykułu jest analiza zależności pomiędzy G_0/M_{DMT} i K_D, gdzie G_0 jest początkowym modułem ścinania, natomiast M_{DMT} i K_D są odpowiednio modułem ściśliwości i wskaźnikiem naprężeń poziomych wyznaczonymi z badań DMT. Zależność ta pozwala na wyznaczenie profilu G_0 wraz z głębokością, ze standardowych wyników badań DMT, co jest przydatne, gdy dostępne są jedynie dane z niesejsmicznych badań DMT. Analizę oparto na dużej liczbie danych dla szerokiego spektrum gruntów o różnej genezie, występujących w Polsce. Zbiór danych obejmowałiły, gliny OC i NC, pyły, piaski średnie, piaski pylaste i piaski drobne. Współczynnik prekonsolidacji (OCR) zostałoszacowany na podstawie danych z testów CPTU i DMT. Uzyskane empiryczne zależności G_0/M_{DMT} vs. K_D porównano z korelacjami ustalonymi przez Marchettiego i innych [1] dla różnych rodzajów gruntu. Aby uwzględnić wpływ prekonsolidacji, na podstawie danych ze wszystkich badanych gruntów drobnoziarnistych zdefiniowano oryginalną zależność empiryczną między G_0/σ'_p i K_D, gdzie σ'_p jest naprężeniem prekonsolidacyjnym.

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