Factors affecting the correlation between cone resistance from CPTU and shear modulus G_0 of sands

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ABSTRACT: One of the factors affecting the initial shear modulus G_0 variation in the subsoil is the overconsolidation effect. Both in Poland and Norway, there are many areas characterized by sand representing both marginal and glacifluvial sediments. The former group is formally included in the normally consolidated, while the latter to the overconsolidated deposits. Marginal deposits may exhibit the overconsolidation effect due to seasonal changes in groundwater levels. The paper presents an analysis of the influence of factors such as porosity, grain size, *OCR*, and vertical (σ_{v0}) and preconsolidation (σ_p) stress on the variability of the G_0 modulus in the sands of the above mentioned geological formations. Results from several dozen SDMT and SCPTU tests have allowed for establishing a general formula describing the relationship between G_0 and the parameters given above, and the so-called local correlation relationships that determine the relationship between of the G_0 modulus and cone resistance q_c.

Keywords: shear modulus G_0, CPTU, non-cohesive soils

1. Introduction

To design and examine the stability of many building structures the knowledge of small strain shear modulus G_0 is required. In the event of a significant variability in the construction of the subsoil found under the designed structure, it is necessary to continuously assess the changes in modulus G_0 of the studied profiles. Such an assessment can be obtained from the empirical correlation between cone resistance q_c from CPTU and small strain shear modulus G_0. Using this correlation to predict changes in modulus G_0 in the subsoil also allows for the reduction of the cost of field tests and reduction of the number of necessary tests used to directly determine modulus G_0 with SDMT and SCPTU. Because of many independent variables which affect the measured parameters in the process of static penetration, unique correlation between cone resistance q_c and shear modulus G_0 does not exist, just as in the case of the interrelationship between undrained shear strength from DMT and CPTU [1]. Therefore, it is interesting to identify factors and their quanttitative impact on the correlation between cone resistance q_c and shear modulus G_0. This issue is the objective of this article. Due to the aforementioned large number of variables affecting cone resistance, the analysis was limited to non-cohesive soils of different genesis and preconsolidation effect.

2. Geological characteristics of test sites

The research was carried out in 6 locations which differed in geological history and allowed the collection of results regarding sediments formed in various depository environments and subjected to various post-sedimentation processes (Fig. 1). Five research sites located in Poland have a complex geological structure. Four of them (Gnojewo, Derkacze, Darłowo and Rzepin) are in the zone of impact of the Weichselian Glaciation, which left moraine deposits covered with fluvioglacial sands.

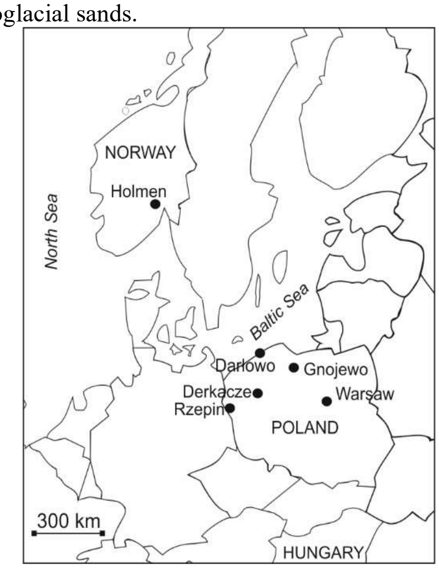

Figure 1. Location of test sites on the map of Europe.

The grain size distribution of the fluvioglacial sands is very diverse and it ranges from gravels to fine and silty sands. The layers are generally thin and do not exceed 1.5 m. However, outwash plain "sandur" forms were formed in stages and over hundred of years, which resulted into a certain variation in the state of these soils and had an impact on the formation of a minor pre-consolidation effect in the subsoil. Overconsolidation ratio (*OCR*) of these soils is estimated within the range of 1-3. The *OCR* values were determined using the Wierzbicki [2] method based on the results of CPTU. The obtained values were randomly compared with geological knowledge regarding the history of these soils.

Older sediments, the so-called interglacial sands found below the layer of the youngest moraine clay, were also examined in two locations (Derkacze and Darłowo). These deposits, which developed into the form of medium and fine sands, are characterized by a homogeneous layer structure and high values of *OCR* reaching 10. The last location, Warsaw, included structures created during the Riss Glaciation. Since the examined fluvioglacial deposits in this region rested on moraine clay, they were geologically normally consolidated. In this case, certain effects of aging (cementation) of the sediment were observed, because the deeper layers showed *OCR* values characteristic for pre-consolidated soils (*OCR* around 6).

Unlike previous locations, the Holmen test site in Norway is characterized by a uniform complex of fluvial sands of fine grain size and thickness up to 20 m [3]. These deposits are normally or lightly over consolidated from a geological point of view. Signs of minor pre-consolidation are the result of changes in the sea level that took place over the last thousands of years and the formation of a layer of a thickened man made ground on the surface. Despite the similar granulometric and mineral composition and thickness these soils significantly differ in origin and degree of coating of grains from those found in Poland.

3. Theoretical foundations of the correlation between cone resistance q_c and shear modulus G_0

The empirical correlation between cone resistance and shear modulus G_0 is built on functional parameters that describe two different processes. One process is the process of static penetration, the other one is the course and registration of a seismic wave in the subsoil. The static penetration process is expressed with Eq. (1) [4, 1].

$$F(P_s, q_c, V_p, Q_1, Q_2) = 0 \tag{1}$$

where: P_s – measured parameter of CPTU test equivalent, q_c, q_t - cone resistance, V_p – penetration velocity, Q_1 – parameter characterising soil medium, Q_2 – parameter characterising cone.

For non-cohesive soils parameter Q_2 is written as a function of multiple variables [5, 6]:

$$Q_2 = f_1(x_1, ..., x_8) \tag{2}$$

where: x_1 – effective unit weight of soil, x_2 – grain size characterisation, x_3 – relative density of soil, x_4 – grain coarseness and agging effect, x_5 –mineralogical type of grain, x_6 – parameter describing stress in the soil, x_7 – parameter defining shear strength (codependent on x_1 … x_5), x_8 – preconsolidation stress or *OCR*.

The quality of the measured cone resistance values also depends on the measurement uncertainty associated with the used test technique [7, 8]. The impact of independent variables recorded in parameter Q_1 on the values of cone resistance and measurement uncertainty cannot be separated [9], hence the change of e.g. cone geometry, penetration velocity and even the use of probes from different manufacturers [7] can lead to different records of the correlation between cone resistance and shear modulus G_0. Equations (1) and (2) justify the statement that there is no unique correlation for non-cohesive soils between cone resistance and modulus G_0. Many authors have documented the impact of variables x_1 … x_n on cone penetration parameters including cone resistance (e.g. [5, 10]).

The function that describes the course and registration of a seismic wave and creates the basis for determining shear modulus G_0 is expressed by a simple Eq. (3) [5]:

$$G_0 = \rho V_s^2 \tag{3}$$

where: ρ – soil density, V_s – shear wave velocity.

Equation (3) is supplemented with Eq. (4), which determines the independent variables that affect shear modulus G or G_0 [11, 12]

$$G / G_0 = f_2(\sigma'_{v0}, e_0, OCR, S, C, K, T) \tag{4}$$

where: σ'_{v0} – effective vertical stress, e_0 – initial void ratio, *OCR* – overconsolidation ratio, *S* – degree of saturation, *C* – grain characteristics, *S* - soil structure, *T* – temperature.

4. Methodology used to obtain the data

Measurement uncertainty, as in CPTU, has an impact on the determined value of G_0. These uncertainties are related to the measurement technique and seismic wave registration. Research by Foti et al. [13] showed high recurrence of seismic wave registration in the replication test for one type of the SDMT dilatometer. A separate issue is the conformity assessment of designated moduli G_0 if the test is performed with two different devices. Such situation took place in the conducted research.

During the research, a cone manufactured by AP vd Berg with an seismic module with a single geophone and a Studio Marchetti dilatometer with a seismic module with a pair of geophones located 0.5 m apart, were used. To determine the time of arrival of the wave in the case of SCPTU, the pseudo interval and cross correlation methods were used. In the case of SDMT, the true interval method and phase shift analysis were applied [14]. Examples of the conducted analysis of the arrival time of the wave are presented in Fig. 2. Determining the time of arrival of the wave allow calculation of the small strain shear modulus G_0 according to the Eq. (3). These results, supplemented with the values of CPTU parameters (q_c, f_s, u_2), formed the basis of the data set used in the analysis (Figs 3 and 4).

The seismic measurements have been done every 0,5 m or 1,0 m of profile (dependently on the testing site). The CPTU data were averaged within defined geotechnical layers and were correlated with the seismic measurements carried out within each particular layer and depth. Data groups from this set, which were correlated with the depths from which samples were taken for laboratory analyzes, were selected for further examination.

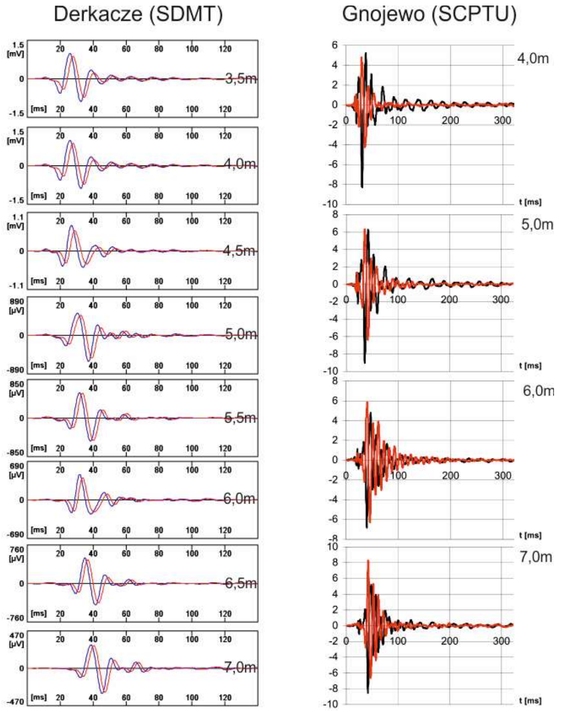

Figure 2. The example of a set of shear vawe readings for SDMT and SCPTU.

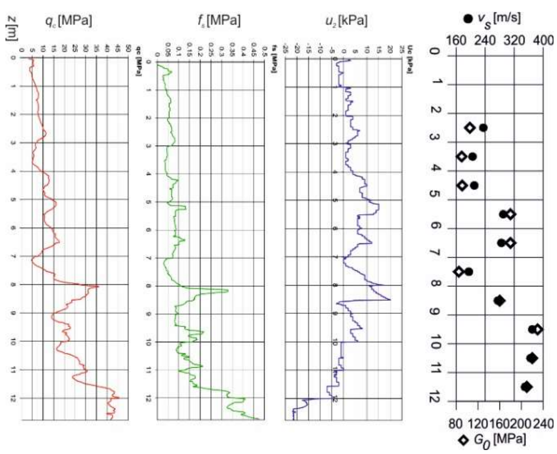

Figure 3. The example SCPTU profile at Gnojewo test site.

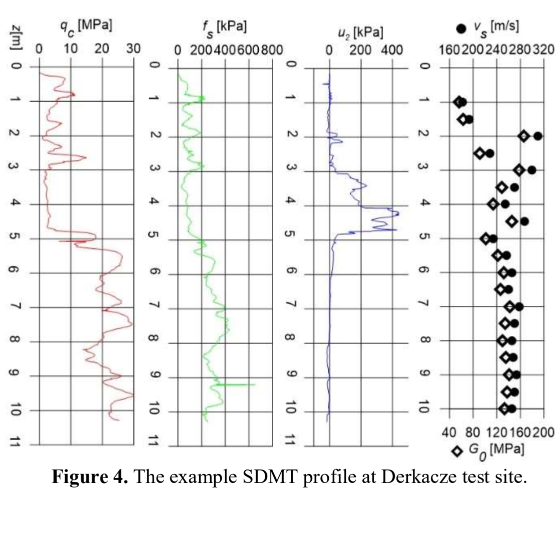

Figure 4. The example SDMT profile at Derkacze test site.

The tests in Holmen sand was carried out in 1983 by Dr. Don Gillespie, formerly University of British Columbia (UBC), Vancouver, using a SCPT penetrometer developed by UBC. This penetrometer had a single seismic arrival sensor. The travel time was defined using the first arrival principle.

The statistical significance of differences between the designated moduli G_0 from both devices can be examined by analyzing the trend of modulus G_0 changes with depth [8]. As far as sediments are concerned, Młynarek et al. [15] showed that the trend of modulus G_0 changes with depth is rectilinear and the trend equation coefficients do not significantly differ in terms of statistics. This type of analysis was carried out for the examined sands and is presented in Fig. 5. The obtained results prove that, SDMT and SCPTU give statistically non-differing assessments of how small strain shear modulus G_0 changes with depth (Fig. 5).

Figure 6 additionally shows the distribution of population of shear moduli G_0 from SCPTU and SDMT in regard to cone resistance q_c, which includes variability of soil grain size, vertical stress, thickness and diversity of origin of non-cohesive soils tested. Figure 6 shows that the modulus values obtained from both studies are located along almost identical trend lines. This fact proves that both techniques consistently register the impact of the parameters listed in equation (4) on the variability of modulus G_0. The obtained result also justifies the possibility of using the value of G_0 obtained from both tests to create a correlation between the shear modulus and cone resistance.

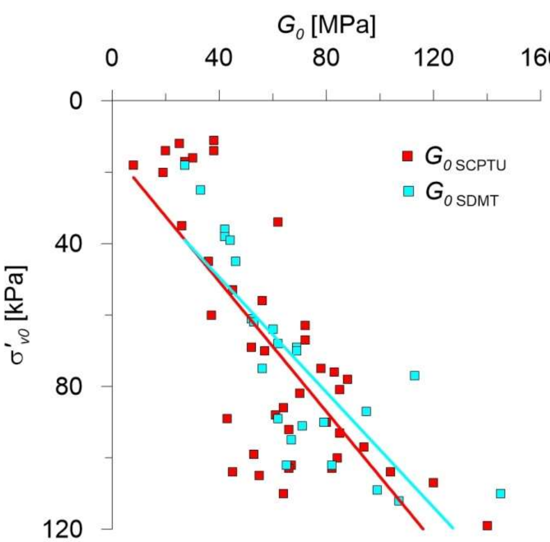

Figure 5. Trend of changes in shear modulus G_0 with depth for SCPTU and SDMT performed in normally consolidated medium sands.

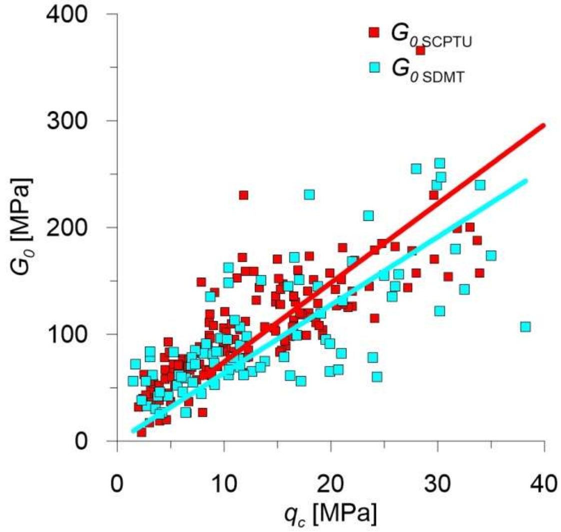

Figure 6. Distribution of shear modulus population G_0 from SCPTU and SDMT with respect to cone resistance q_c.

Several solutions for Eq. (4) are known in the literature. An example of such correlation is Eq. (5) by Jamiołkowski et al. [16].

$$G_0 = 480e^{-1,43}\sigma'^{0,22}_{v0}\,\sigma'^{0,22}_{h0}\,p_a^{0,66} \tag{5}$$

where: p_a - atmospheric reference stress in the same unit as G_0, e – void ratio, σ'_{v0} - effective vertical stress, σ'_{h0} - effective horizontal stress.

In Eqs (1) and (2), and (3) and (4), the same independent variables related to the ground are found. This fact is an accurate justification for the purpose of constructing the correlation for non-cohesive soils between cone resistance and shear modulus G_0. However, an interesting question remains: how do the variables appearing in Eqs (2) and (4) affect the correlation between cone resistance and shear modulus G_0? To answer this question, as mentioned in point 2, research was carried out in several locations in Poland and Norway. The results allowed an analysis taking into account the variables that define grain characteristic, relative density and soil structure. These variables are associated with different sediment genesis and preconsolidation effect. Preconsolidation stress σ'_p, was used to describe the preconsolidation effect, while grain characteristics were taken into account by performing an analysis in four groups of non-cohesive soils, both normally consolidated and pre-consolidated silty sands, fine sands, medium sands and gravels. The second separately analyzed issue was the identification and assessment of the significance of the impact of the variables present in Eq. (4) on shear modulus G_0. This analysis was performed again in various groups of non-cohesive soils and the following variables were taken into account: the degree of thickness instead of the initial void ratio, preconsolidation stress σ'_p and effective vertical stress σ'_{v0}.

5. Analysis of the results

5.1. Analysis of the correlations between cone resistance q_c and shear modulus G_0

An important issue for using the correlations between shear modulus G_0 and cone resistance is the statistical assessment of the significance of this correlation. A certain difficulty for this assessment is the fact that some variables from Eqs (2) and (4) are not written in a discrete form, e.g. ageing, cementation, macrostructure, although they have a significant impact on the value of the coefficient of determination R^2. For this reason, the analysis of the correlation between modulus G_0 and cone resistance was carried out in stages. A set of 238 data from 6 locations was used in the analysis. The first step in the analysis was to examine the basic correlation q_c-G_0, for the entire population (Fig. 7).

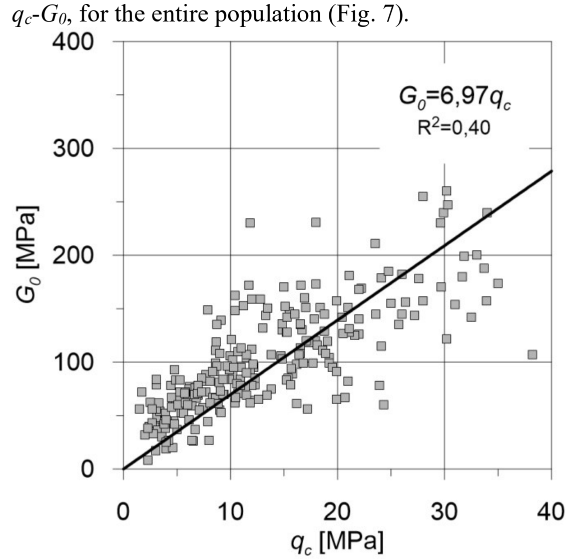

Figure 7. Correlation between shear modulus G_0 and cone resistance q_c for the entire data population.

The correlation between modulus G_0 and cone resistance q_c for the entire population is logarithmic, but its statistical significance is not high. The second step in the analysis was to identify the impact of stress history on the analysed correlation. To this end, using general geological knowledge regarding deposition environments and calculated OCR overconsolidation ratio values, the soils were grouped into normally consolidated and overconsolidated soils. In this step of the analysis a significant improvement in the coefficient of determination R^2 was obtained for normally consolidated soils (Fig. 8).

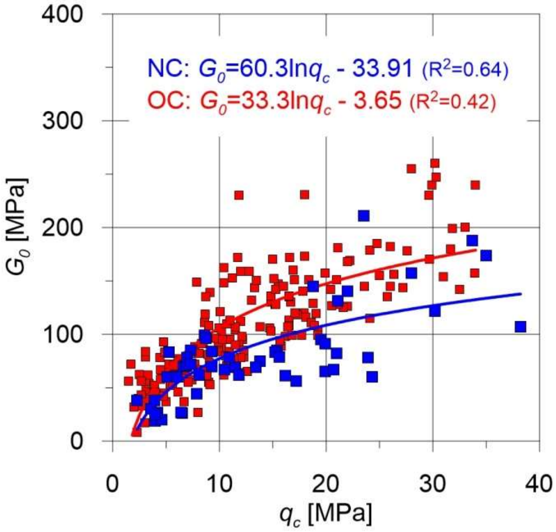

Figure 8. The correlation between modulus G_0 and cone resistance q_c taking into account the division into normally consolidated (blue) and overconsolidated (red) soils.

The third step of the analysis additionally considered the impact on the correlation between the G_0 modulus and q_c cone resistance variables, which define the granulometric composition of the studied soils and their genesis. For this purpose, the data were divided into 5 groups: silty sands (SiSa), fine sands (FSa), fluvial fine sands (FSa Holmen), medium sands (MSa), coarse sands and gravels (CSa & GrSa) (Fig. 9). The set of data of overconsolidated soils were more limited, hence only two groups were distinguished in their case: fine sands and medium sands (Fig. 10).

Figure 9 shows that the normally consolidated fine sands from Holmen are located on the diagram in different part of the plot than the normally consolidated fine sands from Poland. It could be because of a different origin and some diferences between them in angularity. Fluvioglacial sediments from Poland are more sharp-edged, however, the quasi preconsolidation effect present in the Holmen test site soils makes them occupy the upper part of the graph in Fig. 9. This fact is confirmed by the impact of this variable expressed in equation (2) for the mentioned correlation. In most cases the used division allowed to obtain the value of the determination coefficient confirming the significant impact of grain size on the analyzed correlation.

The first and second stage of the analysis showed that the dominant role in the analyzed correlation between shear modulus G_0 and cone resistance q_c is played by both the stress history, which modifies the state of stress, as well as the origin and grain size distribution of soils. In the fourth stage, an attempt was made to create the most versatile model possible determining shear modulus G_0 using multivariable regression analysis. Shear modulus G_0, was adopted as a dependent variable and cone resistance q_c preconsolidation stress σ'_p and soil type and OCR) as independent variables.

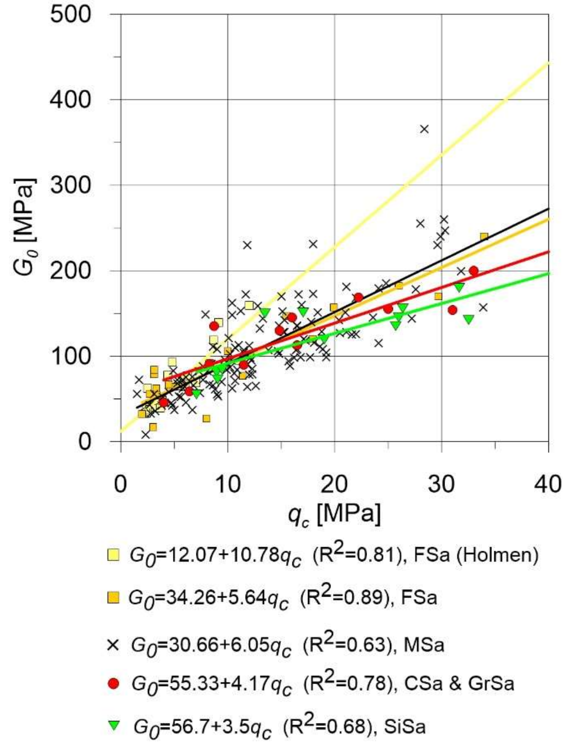

Figure 9. The correlation between modulus G_0 and cone resistance q_c for normally consolidated soils taking into account the type of soil.

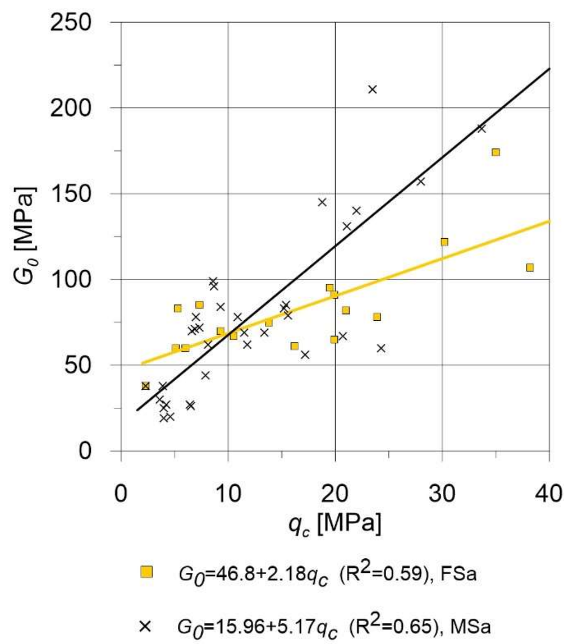

Figure 10. The correlation between modulus G_0 and cone resistance q_c for overconsolidated soils taking into account the type of soil.

Soils with different grain sizes were grouped into normally consolidated and overconsolidated soils in the first part of this analysis. In the case of normally consolidated soils, the analysis includes both the division of soils into individual types and the absence of such a division. The preconsolidation stress σ'_p was calculated according to Eq. (6) [2].

$$\sigma'_p = 0{,}953\mathrm{e}^{0{,}007Q_t} \tag{6}$$

where e is the Euler number, $Q_t=(q_t-\sigma_{v0})/\sigma'_{v0}$.

The following correlations were obtained as a result of the analysis:

- fine sands NC

$$G_0 = 26,197 + 4,146 q_c + 0,103 \sigma'_p \quad (7)$$

R^2=0,85, n=43

- medium sands NC

$$G_0 = 12,238 - 1,816 q_c + 0,463 \sigma'_p \quad (8)$$

R^2=0,71, n=128

- silty sands NC

$$G_0 = 27,316 - 0,089 q_c + 0,239 \sigma'_p \quad (9)$$

R^2=0,83, n=14

- coarse sands and gravels NC

$$G_0 = 73,445 + 2,298 q_c + 0,059 \sigma'_p \quad (10)$$

R^2=0,60, n=11

- fine sands OC

$$G_0 = 46,698 + 2,232 q_c - 0,002 \sigma'_p \quad (11)$$

R^2=0,51, n=17

- medium sands OC

$$G_0 = 17,424 + 3,460 q_c + 0,061 \sigma'_p \quad (12)$$

R^2=0,68, n=25

where: G_0 [MPa], q_c [MPa], σ'_p [kPa].

It is wort to note that the value of σ'_p is obtained from the empirical correlation and in this case maybe strongly influenced by the local conditions. However the use of σ'_p values gives still higher statistical significance level of the correlation with G_0 than σ'_{v0} in the case of analysed set of data.

The obtained values of the determination coefficient R^2 prove that the multivariate dependency model quite well assesses the shear modulus G_0 prognosis based on the cone resistance and pre-consolidation stress for individual soil groups.

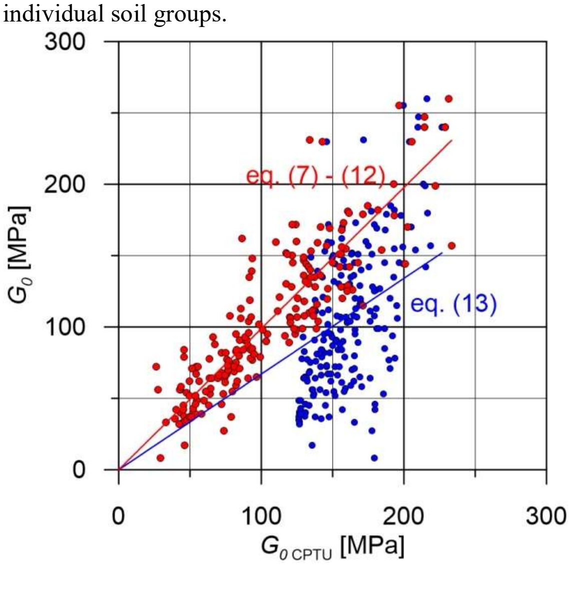

Figure 11. Comparison of G_0 values measured and calculated on the basis of Eqs (7 -12) (red) and Eq. (13) (blue).

The purpose of constructing a multivariate model is also demonstrated by the use of the correlation proposed by Młynarek et al. [17] for overconsolidated clayey sand from Poland Eq. (13).

$$G_0 = 92,16 + 3,21 q_c + 16,8 OCR + 0,103 q_c^2 - \\ - 2,42 OCR q_c + 10,21 OCR^2 \quad (13)$$

R^2=0,42, n=48

Figure 11 shows the location of the shear modulus G_0 values which were calculated in accordance with this correlation. The location of the value G_0 in the lower zone outside the area determined by the values obtained on the basis of Eqs (7-12) also proves the need to construct the so-called local correlations between the shear modulus G_0 and cone resistance taking into account the variables adopted in the regression model.

5.2. Identification of factors affecting shear modulus G_0 variability

The assessment of the impact of soil physical parameters and stress in the subsoil on modulus G_0 was carried out by analyzing partial functions and using multivariate analysis of variance.

The impact of effective vertical stress σ'_{v0} on the modulus G_0 variability is shown in Fig. 12. This figure proves that for the entire population of the determined values of modulus G_0, i.e. for all the soils tested, the division into normally consolidated and overconsolidated soils takes place again. Only in the zone of small G_0 modulus values and small measurement depth (small values σ'_{v0}) the effect of overconsolidation is not significant. This is documented by area A in fig. 12. This effect was also found for the correlation between G_0 and cone resistance q_c. This problem has been presented in point 5.1.

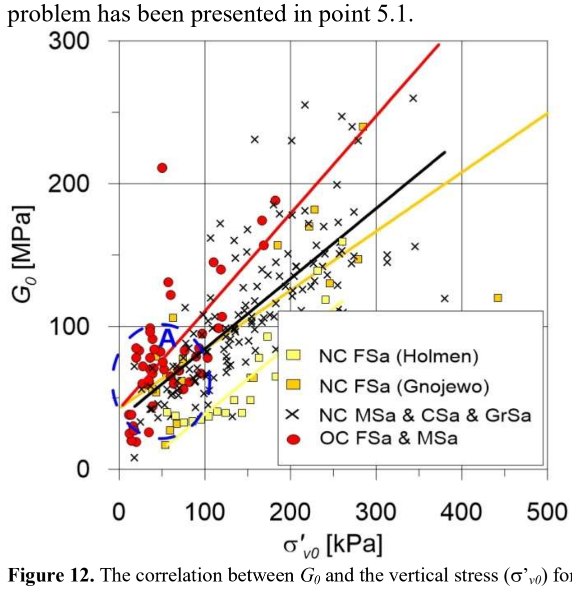

Figure 12. The correlation between G_0 and the vertical stress (σ'_{v0}) for overconsolidated (OC) (red) and normally consolidated (NC) soils distinguishing between fine sands (FSa) from Gnojewo test site (dark yellow) and Holmen test site (light yellow) and medium sands (MSa), coarse sands (CSa) and sandy gravels (GrSa).

Another analyzed partial function was the correlation between modulus G_0 and preconsolidation stress σ'_p . Fig. 13 very clearly documents the impact of preconsolidation stress, i.e. also the genesis of the studied soils, on the G_0 modulus values. Analyzing the partial function $G_0 = f(\sigma'_{v0})$ it can be seen that soils with similar granulation, but deposited in fluvial environments and currently occurring under the sea surface (Holmen test site) can be clearly distinguished from glaciofluvial sediments deposited in the sandur environment (e.g. Gnojewo test site). A different conclusion is obtained from the analysis of the correlation between G_0 modulus with pre-consolidation stress σ'_p. This fact probably confirms the impact of the variable on G_0 modulus, which describes the macrostructure of these deposits in Eq. (4). Another reasons can also be that σ'_p is quite uncertain since it is based on another emprical correlation.

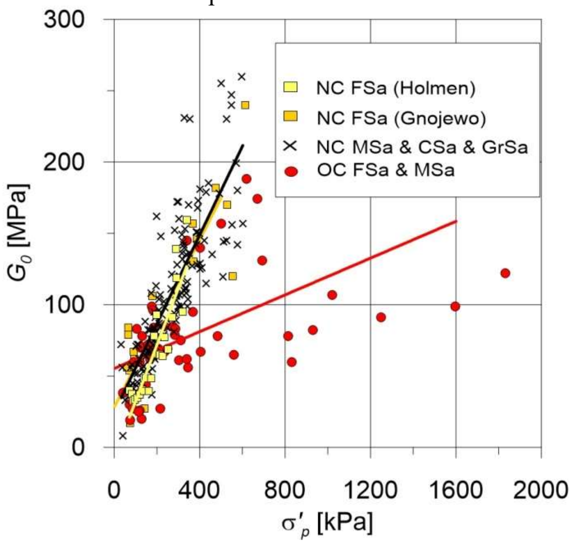

Figure 13. The correlation between G_0 and the preconsolidation stress (σ'_p) for overconsolidated (OC) (red) and normally consolidated (NC) soils distinguishing between fine sands (FSa) from Gnojewo test site (dark yellow) and Holmen test site (light yellow) and medium sands (MSa), coarse sands (CSa) and sandy gravels (GrSa).

Another analyzed partial function is the correlation between modulus G_0 and density ratio D_r. Density ratio was determined from SCPTU using the Jamiołkowski method [6] taking into account the mean stress σ'_{m0}.

$$D_r = \frac{1}{C_2}\ln\left(\frac{q_c}{C_0\left(\sigma'_{m0}\right)^{C_1}}\right) \tag{14}$$

where: σ'_{m0} – average geostatically even stress $(2\sigma'_{h0} + \sigma'_{v0})/3$; correction empirical coefficients $C_0 = 24,94$; $C_1 = 0,46$; $C_2 = 2,96$ –, D_r expressed in %, q_c and σ'_{v0} in bars.

The impact of soil origin is less exposed (Fig. 11) in correlations between modulus G_0 and density ratio. To examine the combined effect of the analyzed variables on modulus G_0 multivariate analysis of variance was used again. Normally consolidated and overconsolidated fine sands were included in one group in order to obtain greater variability in preconsolidation stress σ'_p. The following correlations were obtained for individual soil groups Eqs (15-18):

- fine sands NC & OC

$$G_0 = -17,559 + 112,097D_r + 0,326\sigma'_{v0} + 0,001\sigma'_p \tag{15}$$

$R^2 = 0,67$

- medium sands NC & OC

$$G_0 = -3,879 + 42,351D_r + 0,397\sigma'_{v0} + 0,109\sigma'_p \tag{16}$$

$R^2 = 0,71$

- coarse sands and gravels NC

$$G_0 = 85,219 - 10,604D_r - 0,147\sigma'_{v0} + 0,240\sigma'_p \tag{17}$$

$R^2 = 0,52$

- silty sands NC

$$G_0 = -19,569 + 120,713D_r + 0,249\sigma'_{v0} + 0,024\sigma'_p \tag{18}$$

$R^2 = 0,83$

The analysis of partial regression coefficients shows that the impact of individual variables on modulus G_0 variability is similar, but the level of density ratio is dominant. The proportion of uncontrolled variables, e.g. macrostructure, grain coarseness is much smaller than the correlation between shear modulus G_0 and cone resistance q_c. This is demonstrated by high values of the total determination coefficient R^2, which ranges between 0.54 and 0.84 for individual soil groups.

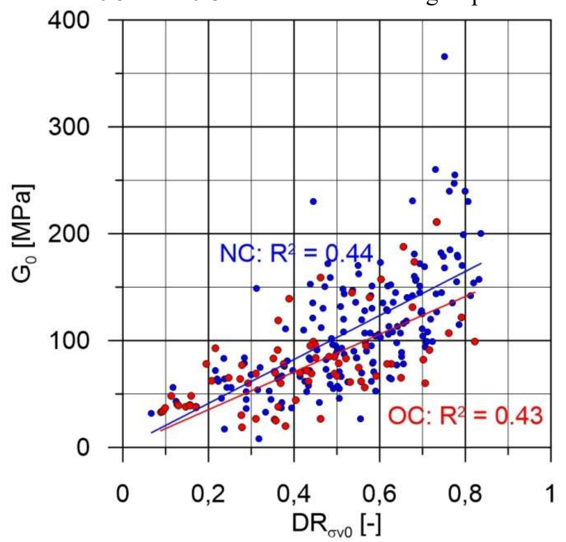

Figure 14. Correlation between G_0 and D_r determined based on Eq. (14) taking into account σ'_m.

6. Conclusions

The conducted tests show that the correlation between cone resistance from the SCPTU method and shear modulus G_0 is an effective way to determine changes in this modulus in a non-cohesive subsoil. However, the documented effect of many variables on this correlation results in the need to construct this correlation for individual soil groups because of their grain size and their origin. Taking these variables into account makes it possible to obtain a statistically very favorable assessment of the correlation between cone resistance and shear modulus G_0. Equations (7–12) can be recommended for geotechnical design, as long as they are applied locally. The effect of soil genesis can be taken into account to some extent using overconsolidation ratio OCR or effective preconsolidation stress σ'_p. Test results also confirmed the strong correlation between modulus G_0 determined from SCPTU and SDMT and soil physical parameters and stress in the subsoil. It is necesarry to emphasize that still the best solution is to carry out SCPTU/SDMT to have less uncertainies in G_0.

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