Geotechnical Parameters of Loess Soils from CPTU and SDMT

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ABSTRACT: The article presents the results of geotechnical in situ tests of loesses in the area of Łańcut. Static penetration tests (CPTU) and seismic dilatometer tests (SDMT) enabled to determine deformation and strength parameters of subsoil. Relationships between shear modulus G_0 from the seismic test, overconsolidation stress, constrained deformation modulus and undrained shear strength have been determined and analyzed. The obtained results allowed to distinguish two zones in the loess subsoil: the quasi-overconsolidated upper zone and the normally consolidated lower zone. In both zones different types of relationship between the results from CPTU and from SDMT have been observed. Recommendations for the interpretation of the results from CPTU and SDMT tests in loess deposits have been proposed

1 INTRODUCTION

In Poland the subsoil comprises soils of many geological formations of greatly diverse genesis. Geotechnical parameters in some of these deposits have been well identified thanks to extensive in situ tests and laboratory analyses. At present static penetration and dilatometric tests are considered to be the leading in situ testing methods. In the case of subsoil, which is composed of eolian soils, we face a considerable challenge if the above mentioned methods are used to determine strength and deformation parameters. Only a very limited number of studies have been devoted to these soils both in world and Polish literature on the subject. Based on available literature it may be stated that several issues need to be discussed in the aspect of both basic and applied research. These problems include:

- the effect of macrostructure on parameters measured in CPTU and SDMT, as well as the determination whether the macrostructure in the loess subsoil profile is homogeneous. Studies on silty alluvial deposits (Stefaniak, 2014) showed that the subsurface layer of the subsoil is characterized by cementation zones and a marked preconsolidation effect; the assessment of consistency of loess genesis with the degree of preconsolidation in these soils, as well as the potential identification of the effect of preconsolidation using CPTU and DMT classification systems;
- the assessment of applicability of formulas from CPTU, established for cohesive soils of a different genesis, to determine undrained shear strength and constrained moduli during primary consolidation;
- identification of factors affecting constrained moduli, determined from CPTU and SDMT and establishment of an empirical dependence, which specifies the relationship between these moduli;
- determination of the relationship between shear modulus G_0 determined from SDMT and parameters from CPTU and DMT.

The aim of this paper is to discuss the above mentioned problems on the basis of studies conducted on loess subsoil in the southern part of Poland.

2 GEOLOGICAL CHARACTERISTICS OF THE STUDY AREA

In situ tests were conducted in the area of Łańcut, located on the western edge of a vast belt of loess cover of the Podolian Upland, stretching to that part of Poland from Ukraine, (Bogucki et al. 2014). The thickness of the loess cover varies in this region, ranging from 9 to approx. 20 m (SMGP) (Fig. 1).

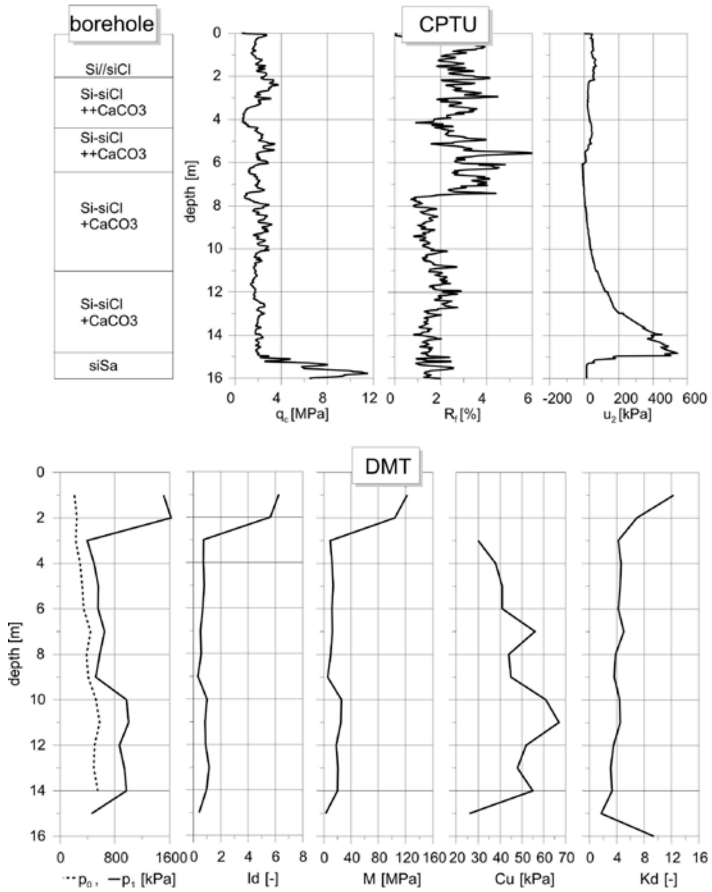

Fig. 1. Results of CPTU and DMT in view of the geotechnical profile of an example testing node

These soils, formed in the Middle and Upper Pleistocene, lie on older glacial and fluvioglacial deposits, connected with the Mindel glaciations. Investigated soils have slightly elevated contents of fractions in relation to typical grain size distribution of loess soils found in south-eastern Poland (Frankowski et al., 2010) (Tab. 1). In terms of granulometry analyzed loesses are silts, sandy silts and occasionally silty loams, i.e. soils corresponding to PN-ISO soils from the class of silty-loamy and sandy mixtures (saSi –siCl) according to ISO standards (Tab. 1).

Table 1. Mean contents of individual fractions of investigated loess soils in relation to typical values given by Frankowski et al. (2010) (LI- liquidity index).

Fraction	Sand [%]	Silt [%]	Clay [%]	LI
Łańcut study site	27,2	60,5	12,3	0,17-0,48
Typical range	1,8-29,7	61,6-91,5	3,9-9,9	

In the case of tested loess soils individual fractions fell within the following ranges: 24-33% sand, 55-71% silt, 7-14% clay fraction. In the loess series the soil water is found only sporadically and it is only in the form of local seepage. The underground water table is connected with fluvioglacial deposits, underlying loess soils and takes the form of a perched water table with an amplitude of several meters.

Frankowski et al. (2010) and Bogucki et al. (2014) indicated that the loess profile in the Podolian Upland is at least bipartite. The roof of the profile (according to Frankowski et al. 2014 – to a depth of approx. 3 m) is characterized by greater dipping both at geostatic stress and at additional loads. The bottom zone of the soil profile, despite a similar genesis and grain size composition, is less porous, has a greater moisture content and markedly lower dipping (Frankowski et al. 2010). Both zones probably differ in age (Bogucki et al., 2014) as well as the effect of postgenetic processes connected with changes in moisture content and a slow settlement of the structure under the influence of the mass of the overlayer (Frankowski 1978). An additional element influencing the variation in the loess profile is probably also connected with the presence of a strong carbonate cementation in the roof section of the deposits, also typical of alluvial silty deposits (Stefaniak 2014) (Fig. 2).

Investigations conducted by Stefaniak definitely showed that the cementation zone is characterized by three elements:

- very high heterogeneity of the macrostructure (Fig. 2),
- increased rigidity in comparison to the subsoil zone outside the range of cementation,
- the effect of quasi-preconsolidation.

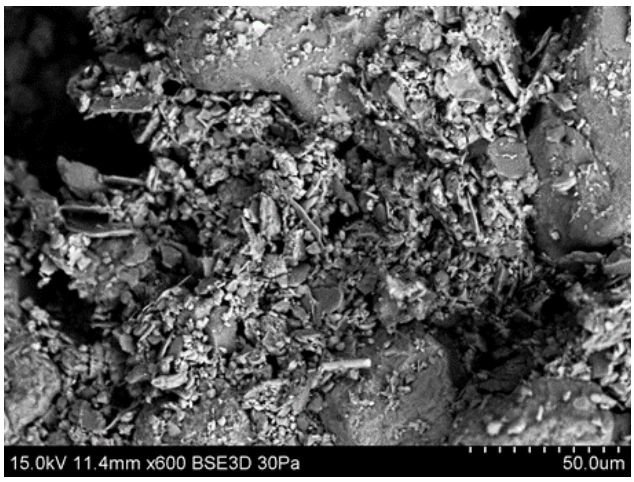

Fig. 2. The presence of carbonate cementation in silty deposits (after Stefaniak 2014).

The presence of the quasi-preconsolidation effect in the roof section of loess soils very well documents the position of these soils in the Robertson's classification system (CPTU) (Fig. 3). Some loess soils, from the deeper subsoil section, represent normally consolidated deposits, which is formally consistent with their genesis. The location of investigated loess soils in the classification systems proposed by Robertson and Marchetti-Craps shows high spatial variation in grain size of loess soils.

3 SCOPE OF STUDY

In situ tests were conducted in nodes, in which test boring combined with sampling, static penetration (CPTU) and the test with a seismic dilatometer (SDMT) were performed. Static penetrations were performed using a Hyson 200kN penetrometer by a. p. van den Berg, while dilatometer tests were conducted using an original dilatometer by Prof. Marchetti's Studio. In the course of tests standard parameters were recorded, making it possible to determine the basic testing parameters: p_0, p_1, v_s (SDMT) and q_t, f_s, u_2 (CPTU). These parameters, supplemented with data from testing profiles concerning lithology, soil density, geostatic stress and hydrostatic pressure made it possible to determine derivative parameters from both tests, i.e. K_D, E_D, I_D (SDMT) and Q_t, F_R, q_{t1} (CPTU). Derivative parameters were established based on the standard formulas given e.g. by Marchetti (1980) and Lunne et al. (1997) and Robertson (2009).

Due to the scarce literature sources on the interpretation of CPTU and DMT testing several empirical dependencies were used in order to obtain the most advantageous statistical evaluation of the relationship between parameters provided by CPTU and DMT, and the constrained modulus M and shear modulus G_0 as well as undrained shear strength s_u (c_u). These dependencies are formulated for cohesive soils. For this purpose the following dependencies were used:

- shear modulus:

$$G_0 = \rho\, v_s^2 \quad (1)$$

- preconsolidation pressure

$$\sigma'^{CPTU}_p = \sigma'_{v0}\ (5.42\ln Q_t + 14.97) \quad (\text{for } I_p \approx 10)$$

Wierzbicki (2010) (2)

- undrained shear strength

$$s_u^{CPTU} = (q_t - \sigma_{v0})/N_{KT}$$

, N_{KT} for silts was adopted after Stefaniak (2014) (3)

$$s_u^{DMT} = 0.22\ \sigma'_{v0}\ (0.5K_D)^{1.25}$$

Marchetti (1981) (4)

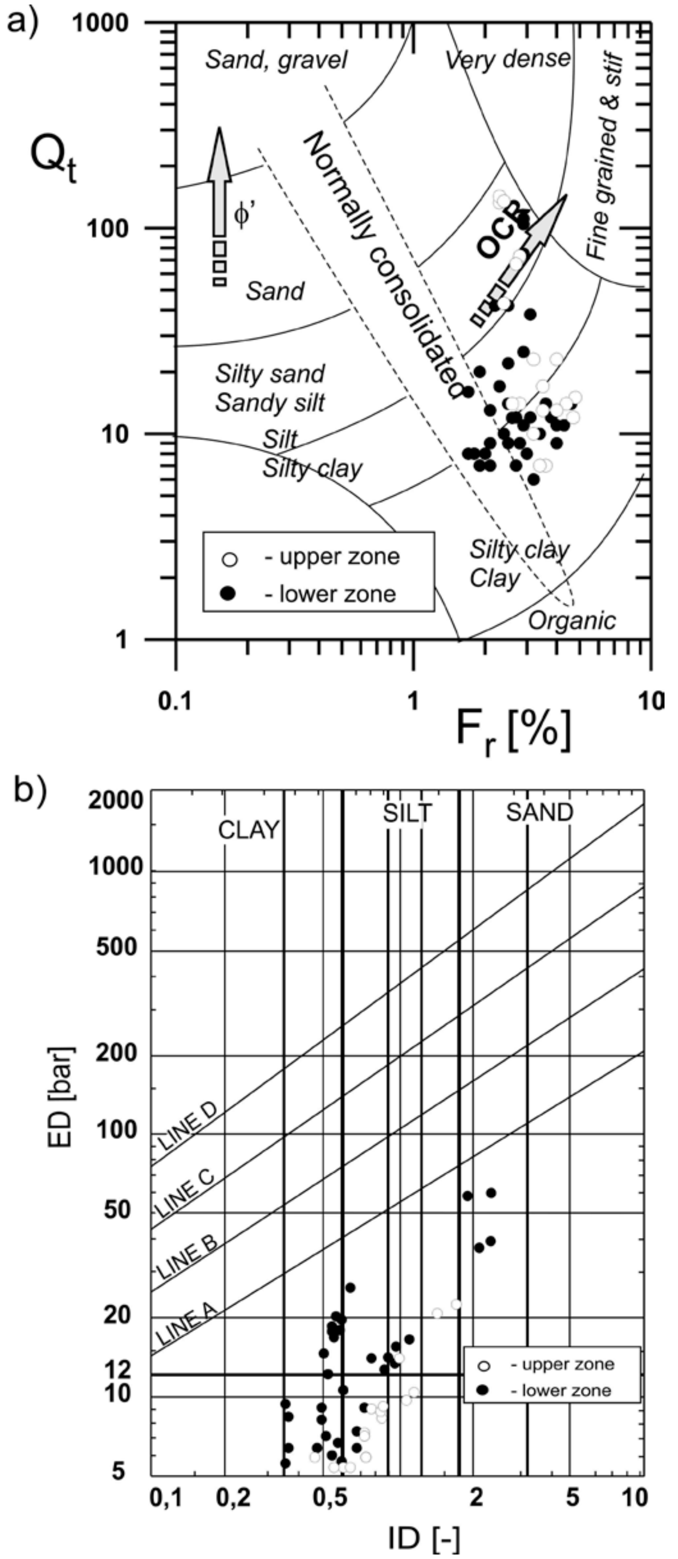

Fig. 3. Position of tested loess soils in the CPTU classification system by Robertson (1990) (a) and the DMT classification system by Marchetti-Craps (1981) (b).

s_u values were also established alternatively from the formula

$$s_u^{DMT} = 0.164\ \sigma'_{v0}\ K_D^{0.345}\ ((p_1 - u_0)/\sigma'_{v0})^{0.544}$$

(Galas 2014) (5)

- constrained modulus during primary consolidation corresponds to the oedometric modulus:

$M^{CPTU} = 8.25(q_t - \sigma_{v0})$ (Mayne 2005) (6)

$M^{DMT} = R_M\ E_D$, for R_M determined according to Marchetti (1981) (7)

4 MECHANICAL PARAMETERS OF LOESS SOILS FROM SDMT AND CPTU

A key issue in the determination of mechanical parameters of loess soils using CPTU and DMT is to identify factors which affect measured parameters in both tests. In order to identify these factors we may apply functions which describe the process of static penetration and dilatometric tests in cohesive and organic soils, as was discussed in details by Młynarek (1978) and Młynarek et al. (2007, 2008).

In the case of loess soils it is worth to emphasize that a particularly important role in the determination of the influence on parameters measured in CPTU and DMT, is played by the macrostructure and the cementation effect. A very good identification of influence of cementation on CPTU and DMT characteristics may be obtained by the evaluation of variability of mechanical parameters in the loess subsoil profile. A particularly effective identification will be provided when the other variables in the profile are well known (e.g. proportions of grain size fractions and moisture content remain similar). Such a situation was observed throughout the entire study area of loess subsoil. However, the relatively limited variation of these parameters will cause fluctuation of points on graphs, which will describe correlations between parameters from CPTU and DMT. Thus it is particularly advisable to perform two different tests to identify the effect of a structural change on mechanical parameters of loess soils, since CPTU and DMT exhibit different testing kinematics, different directions of measurements, a different deformation scale during cone penetration in the subsoil, as well as different testing conditions in relation to the ultimate limit state of soil (Mayne, 2005). Such an approach was applied in the analysis of testing results.

4.1 *Shear modulus G_0*

Lee and Stokes (1986) and Jamiolkowski et al. (1995) systematized factors affecting shear modulus G_0. These factors are presented in the original form of the dependence (11).

$G_o = f(\sigma'_{v0}, e_0, OCR, Sr, C, K, T)$ (11)

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

A change in the OCR value may be replaced by the value of preconsolidation pressure σ'_p. Differences in the significance of the effect of individual factors on modulus G_0 causes strong locality of empirical dependences used in the assessment of G_0. This may occur especially in soils with an exposed macrostructure, such as loess soils. In the analysis of hierarchy of the effect of these variables on modulus G_0 the multivariate analysis of correlation was applied, in which results of CPTU and SDMT testing were used. It results from this analysis that σ'_{v0} and $\sigma'_p{}^{CPTU}$ and liquidity index were statistically significant independent variables. The limited significance of the effect of the other variables, such as grain size distribution, resulted from their relatively low variability in the profile, which was commented on in point 3.

The shown significant effect of variables σ'_{v0} and $\sigma'_p{}^{CPTU}$ indicates the bipartite character of the analyzed loess soil profile (Figs. 4 and 5). The boundary between these zones may be located at a depth within the range from 4 to 5 m. Variability in rigidity of these two zones is perfectly evident in the analysis of correlation for σ'_p values determined from CPTU and G_0 values (Fig. 5).

The effect of the quasi-preconsolidation effect on the varied rigidity of individual subsoil zones may also be investigated by assessing the relationship between the dimensionless coefficient $G_0 \cdot M^{DMT-1}$ and the coefficient K_D from DMT. Results recorded for the tested loess soils are arranged along the

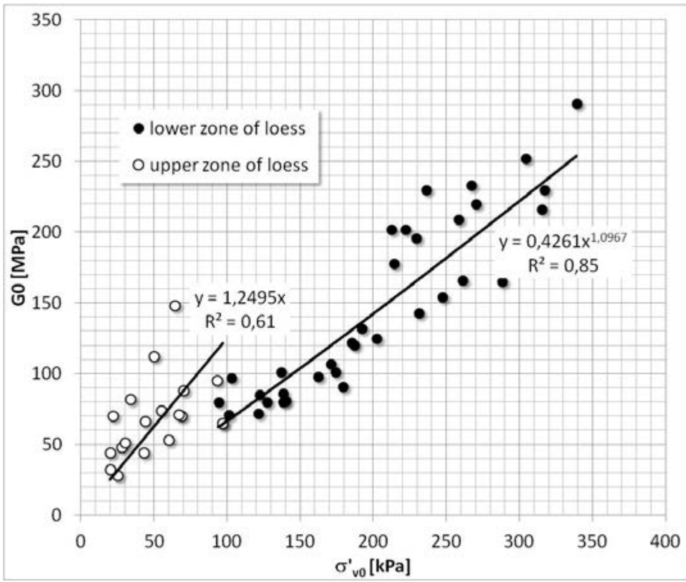

Fig. 4. Relationship between shear modulus G_0 and σ'_{v0}, in the upper and lower zones of the loess soil profile.

relationship determined for such soils by Dusan et al. (2014); however, they do not make it possible to accurately separate the upper and lower zones in the investigated profile (Fig. 6). This fact is caused by the high heterogeneity of the macrostructure of the upper zone and high measurement uncertainty in the assessment of modulus M^{DMT}. This element was commented on in point 4.2.

Recorded results confirm the adopted assumption that in the tested soils in the subsurface zone of the subsoil profile we observe a marked effect of quasi-preconsolidation processes on properties of the loess soil and its macrostructure. Frankowski (1978) explained that quasi-preconsolidation processes to a considerable degree are connected with cementation of loess soil in this subsoil zone. Such a conclusion confirms a comparison of values of the dimensionless coefficient G_0/q_c with values of parameter q_{c1} (Fig. 7). The obtained definite division

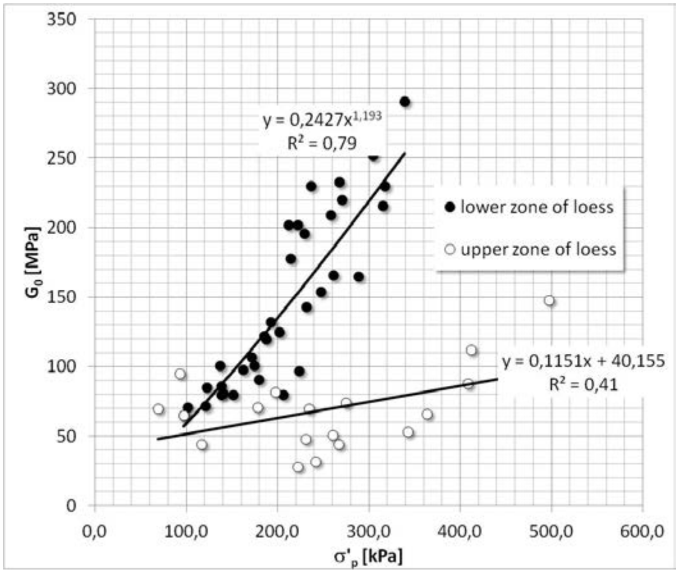

Fig. 5. A relationship between the shear modulus G_0 and preconsolidation pressure σ'_p in the upper and lower zones of the loess soil profile.

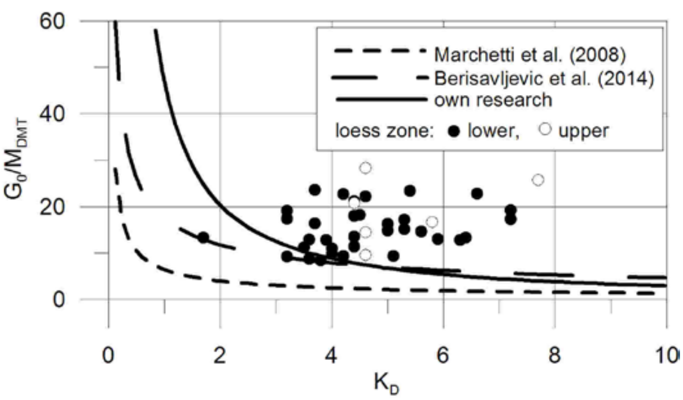

Fig. 6. Relationship between dimensionless coefficient $G_0 \cdot M^{DMT-1}$ and the coefficient K_D.

of the results into two groups is consistent with the results reported by Dusan et al. (2014) for loess soils in Serbia. Also in this case soils with dipping characteristics exhibit a lesser value of G_0/q_c and a higher value of q_{c1}. This fact is confirmed by the diverse macrostructure of the upper and lower zones of the investigated loess subsoil. A certain shift observed in the case of loess soils in Serbia and Poland in the above mentioned dependence indicates the need to consider specific, regional properties of loess soils.

4.2 *Constrained deformation modulus M*

As it is generally accepted, the determination of constrained moduli during primary consolidation, which correspond to the oedometric modulus in the case of CPTU and DMT, is based on different concepts. In CPTU empirical dependencies are used to determine modulus M due to the fact that measurement of cone resistance is recorded in the ultimate limit state. Values of pressures p_0 and p_1 in DMT are recorded at small deformations Thus, it is experience that makes it possible to directly determine the constrained modulus.

The constrained modulus depends on several variables and for this reason the basis for the determination of the constrained modulus during primary consolidation M from DMT is provided by the dilatometric modulus E_D and empirical formulas given by Marchetti. Soil macrostructure is an important factor affecting moduli determined from

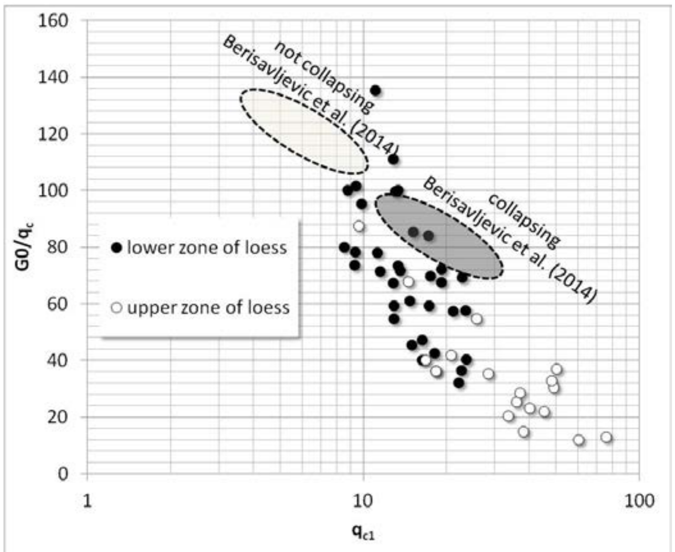

Fig. 7. Identification of the dipping zone of loess soils in view of the results reported by Berisavljevic et al. (2014), $q_{c1} = (q_c/p_a)(p_a/\sigma'_{v0})^{0,5}$.

CPTU and DMT. This factor was strongly manifested in analyzed loess soils. In Fig. 8 we may observe a lack of statistical correlation between moduli from both tests in the upper zone of the loess subsoil. This fact has been influenced by several factors:

- The upper zone is strongly heterogeneous due to the effect of cementation. Zones of stabilization by cementation are locally spatially varied. Results of point-specific DMT are thus strongly dependent on the macrostructure and rigidity of this zone,
- Fluctuations of points in Fig. 8 are also connected with local changes in grain size composition in this zone and the state of consistency.

It needs to be stressed that the identical effect of the assessment of variation for moduli M^{DMT} and M^{CPTU} was recorded in the cementation zone by Stefaniak (2014) in alluvial silts. Rigidity in this zone may be geotechnically defined by mean values of moduli M. Mean values of moduli M from both tests are M^{CPTU} = 19 MPa and M^{DMT} = 14 MPa, respectively.

A completely different description of subsoil rigidity using CPTU and DMT may be obtained for the lower zone of the loess subsoil. A lack of the effect of cementation and a relatively homogeneous macrostructure in this subsoil zone facilitates a good description of the change of rigidity in this zone with the change in geostatic stress σ_{v0} using moduli M^{DMT} and M^{CPTU}. If DMT is assumed to be the reference to CPTU, then Fig. 9 indicates that a calibration test may be conducted for both moduli (Młynarek et al. 2012).

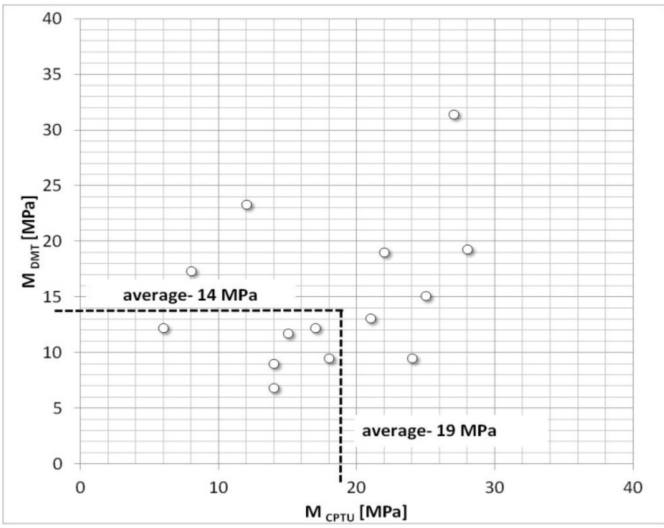

Fig. 8. A relationship between constrained moduli from CPTU and DMT for the upper zone of the loess subsoil.

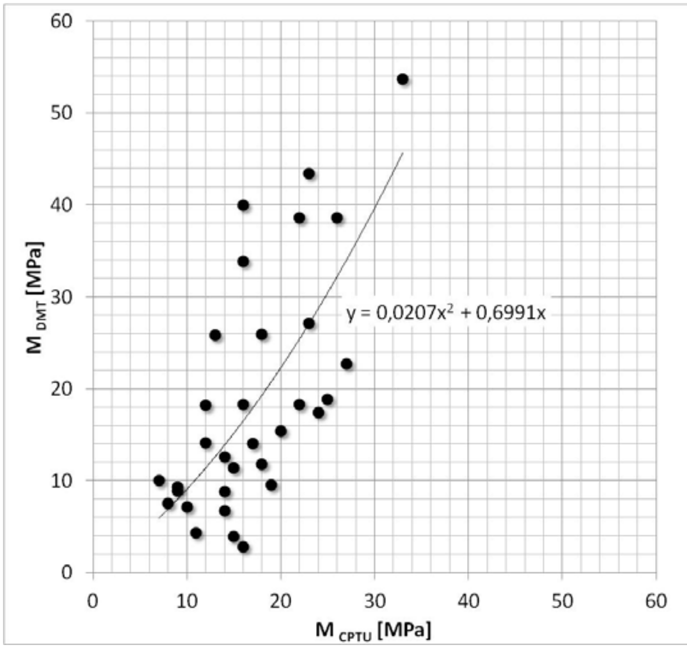

Fig. 9. A relationship between constrained moduli from CPTU and DMT for the lower zone of the loess subsoil.

The obtained correlation between moduli from both tests is presented in Fig. 9. The formula for this correlation has the form (12):

$$M^{DMT} = 0{,}021 M_{CPTU}^{2} + 0{,}7\, M_{CPTU} \quad (12)$$

4.3 *Shear strength parameters*

In order to determine values of undrained shear strength (s_u) from CPTU and DMT, in contrast to the estimation of the constrained modulus, CPTU is considered to be a reference test. The value of coefficient N_{kt} is a parameter from the solution of a theoretical task for the model of cone penetration into the subsoil (Lunne et al., 1997). In the conducted analysis values of coefficient N_{kt} were assumed after a study by Stefaniak (2014). These values were N_{kt} = 7.5 for the cemented zone of alluvial silts with the effect of preconsolidation and N_{kt} = 14.2 for the normally consolidated zone of alluvial silts. Values of these coefficients were verified by Stefaniak in triaxial compression tests. The application of the formulas proposed by Marchetti (5) and Galas (6) did not lead to significant differences in the assessment of undrained shear strength in loess soil in the two main subsoil zones. Fig.s 10 and 11 present a relationship between undrained shear strength determined from CPTU and DMT.

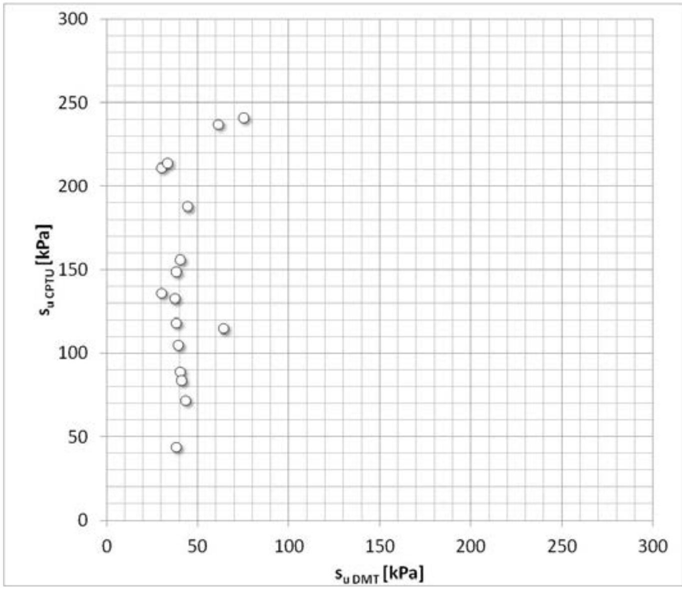

Fig. 10. A relationship between undrained shear strength from CPTU and DMT (the upper zone of the loess subsoil).

Interpretation of these results is analogous to that in the assessment of changes in subsoil rigidity in the upper and lower zones of the loess subsoil. Factors specified in the description of the constrained modulus M in the upper zone caused an identical effect, i.e. a lack of correlation between obtained results. In contrast to CPTU, no changes were recorded in S_u values from DMT with a change in the vertical geostatic stress. This fact is perfectly documented in Fig. 12.

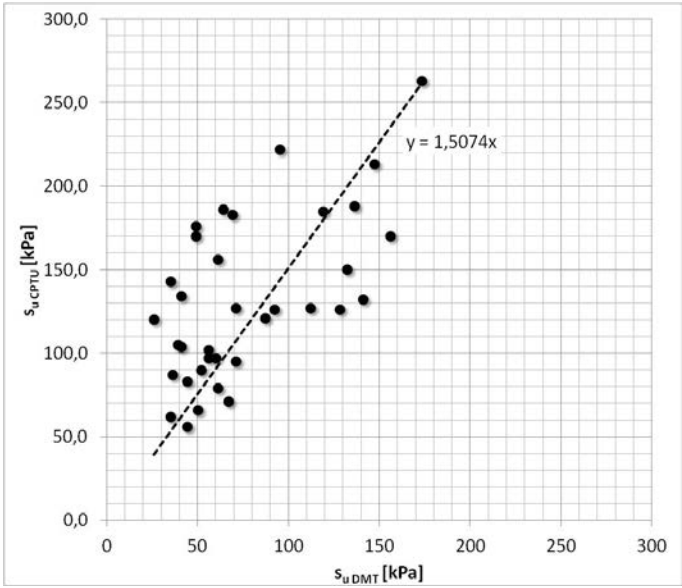

Fig. 11 A relationship between undrained shear strength from CPTU and DMT (the lower zone of the loess subsoil)

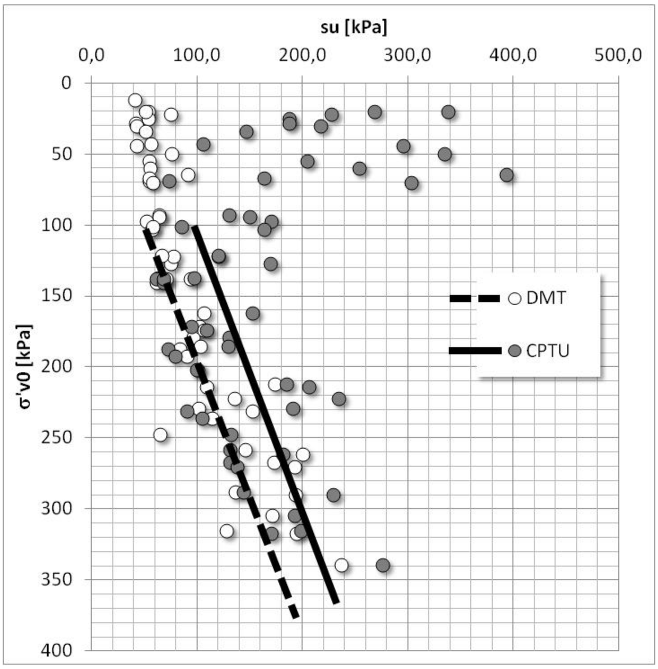

Fig. 12. Change in values of shear strength s_u from DMT and CPTU depending on the vertical geostatic stress σ_{v0}.

A completely different situation is found in the lower zone (Fig.12). Values of s_u both from CPTU and SDMT show a characteristic, rectilinear trend with a change in the vertical geostatic stress σ'_{v0}. Geometry of such a trend in normally consolidated deposits has been documented in numerous studies (e.g. Lunne et al., 2007; Mayne, 2006; Robertson, 2009; Stefaniak, 2014). Fig. 12 documents high effectiveness, particularly for CPTU, in the assessment of changes in shear strength of loess soils in that zone. Following the suggestion by Marchetti (1999), DMT requires calibration, adapted to the type of soil and its genesis. Fig. 11 presents assessment of consistency of s_u from both tests following calibration. The calibration line makes it possible to correct formula (5) to the form:

$$s_u^{DMT} = 0.33\ \sigma'_{v0}\ (0.5\ K_D)^{1.25} \qquad (13)$$

The trend shown in Fig. 12 for changes in values of s_u^{DMT} concerns non-calibration values.

A significant problem concerning the use of DMT results to derive the s_u values in the upper, cemented part of loess profile can be clearly seen comparing the K_D values from DMT and reference s_u values (Fig. 13). The trend for upper part is different than for the lower one and is much more lower consistent than for the lower part of loess.

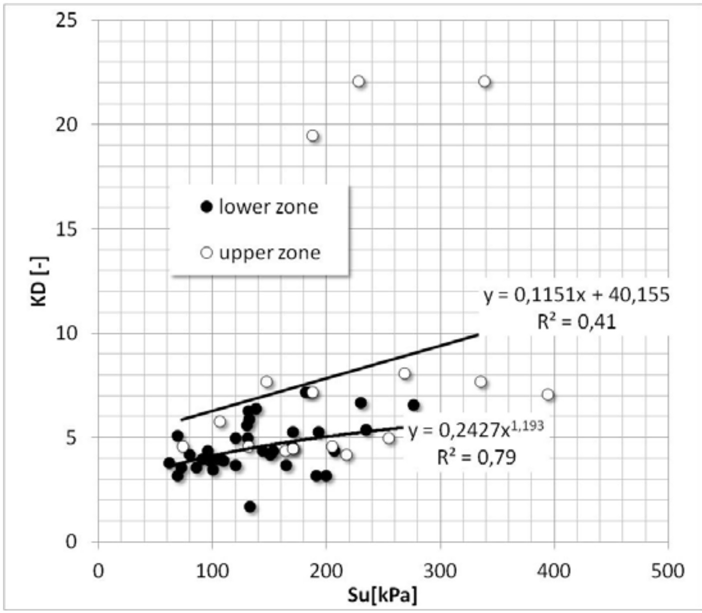

Fig. 13. Relationship between undrained shear strength s_u from CPTU and horizontal stress index K_D from DMT on the background of location within the loess zone

5 CONCLUDING REMARKS

Subsoil composed of loess soils represents formally genetically homogeneous deposits. However, numerous geological processes have caused considerable spatial diversification in the macrostructure and as a consequence – in the properties of these deposits. Additional factors which affect variation in mechanical parameters of subsoil include those connected with the effect of quasi-preconsolidation and probably cementation. Obviously further studies will be required to explain the occurrence of these effects. Static probing and dilatometric tests proved to be very effective methods to identify zones in the subsoil with definitely diverse properties. A strongly diverse macrostructure in the two zones of the subsoil resulted in the need to verify - through calibration – the standard formulas for the determination of constrained moduli and undrained shear strength in both zones.

The classification system proposed by Robertson also proved useful in the preliminary identification of the effect of normal consolidation and quasi-consolidation. These effects were confirmed by CPTU.

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