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Geotechnical Parameters of Alluvial Soils from in-situ Tests

Zbigniew Młynarek, Katarzyna Stefaniak, Jędrzej Wierzbicki

Poznań University of Life Sciences, Department of Geotechnics, ul. Piątkowska 94, 60-649 Poznań,
e-mails: zbigniew.mlynarek@hebo-poznan.pl, kst@up.poznan.pl, jw@up.poznan.pl

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Abstract

The article concentrates on the identification of geotechnical parameters of alluvial soil represented by silts found near Poznań and Elbląg. Strength and deformation parameters of the subsoil tested were identified by the CPTU (static penetration) and SDMT (dilatometric) methods, as well as by the vane test (VT). Geotechnical parameters of the subsoil were analysed with a view to using the soil as an earth construction material and as a foundation for buildings constructed on the grounds tested. The article includes an analysis of the overconsolidation process of the soil tested and a formula for the identification of the overconsolidation ratio OCR. Equation 9 reflects the relation between the undrained shear strength and plasticity of the silts analyzed and the OCR value. The analysis resulted in the determination of the N_{kt} coefficient, which might be used to identify the undrained shear strength of both sediments tested. On the basis of a detailed analysis of changes in terms of the constrained oedometric modulus M_0, the relations between the said modulus, the liquidity index and the OCR value were identified. Mayne's formula (1995) was used to determine the M_0 modulus from the CPTU test. The usefullness of the sediments found near Poznań as an earth construction material was analysed after their structure had been destroyed and compacted with a Proctor apparatus. In cases of samples characterised by different water content and soil particle density, the analysis of changes in terms of cohesion and the internal friction angle proved that these parameters are influenced by the soil phase composition (Fig. 18 and 19). On the basis of the tests, it was concluded that the most desirable shear strength parameters are achieved when the silt is compacted below the optimum water content.

Key words: silty soils parameters, strength, deformation, CPTU, SDMT

1. Introduction

The structure of subsoil in many European countries, including Poland, is highly complex. This results from numerous geological processes, which have occurred in those countries. A considerable part of the subsoil structure is composed of alluvial deposits, particularly in the coastal zone of the Baltic Sea, as well as in vast ice-marginal valleys of rivers and glacial channels. The recognition of properties of these deposits is a research problem yet to be solved. Two issues related to these soils were emphasized in a report on the application of the cone penetration test (CPTU) in East European countries (Młynarek 2010). One of them is the evaluation of the properties of these soils, and above all the interpretation of characteristics determined by in situ studies when these soils constitute a foundation for earthen structures. The other problem is the use of these soils as material for earthen structures. Another interesting issue in the evaluation of mechanical parameters of alluvial soils from the group of silts is the effect of overconsolidation on the interpretation of characteristics determined by in-situ testing and the evaluation of their mechanical parameters. The effect of macrostructure and sensitivity of these soils is also stressed during the investigations. In order to clarify these issues, analyses were conducted on normally consolidated alluvial deposits, found in the areas of Elbląg (northern part of Poland) and Poznań (central part of Poland). Moreover, an example was presented concerning the effect of the overconsolidation of alluvial deposits on their position in the CPTU and DMT classification systems. In the evaluation of properties of selected deposits in the geostatic state of stress (in situ), the following methods were used: cone penetration test (CPTU), vane test (VT) and dilatometer test (DMT). The results of those tests are presented in this article.

2. Alluvial Deposits as a Foundation for Earthen Structures

2.1. Genesis of the Soils Tested

Alluvial deposits comprise a very broad spectrum of soils, both in terms of the type and condition of soil. This results from the facies variation of the river valley system at the cross-section and particularly along the river course. With the increasing distance from the river head, rivers transport and deposit increasingly fine material, sometimes containing considerable admixtures of the organic fraction. In Central European Lowlands and the Baltic Coastland, glaciation and deglaciation processes occurring in the Pleistocene had an additional effect on the presence of alluvial soils with a silt fraction. As a consequence, we frequently observe silty packing of longitudinal depressions, being former drainage channels of the ice-sheet forefield. Apart from the dominant content of the silt fraction, a common characteristic of these soils is their occurrence in the stratigraphic position characteristic of normally consolidated soils.

In terms of its geology, the experimental testing site in the area of Poznań is the remnant of the meridian course of drainage of the Vistula glaciation ice-sheet. Waters of the melting ice-sheet were in some cases discharged along small depressions. In the case of flows with a low water energy those waters carried mostly material corresponding to silt and clay fractions, almost over the surface of older glacial tills and fluvioglacial sands. Such deposits vary in thickness, ranging from layers of around a dozen to several dozen centimeters up to complexes of deposits several meters thick. Deposition under periglacial conditions and the vicinity of the ice-sheet resulted in a relatively small proportion of organic admixtures, as well as considerable contents of calcium carbonate, characteristic of Pleistocene soils genetically connected with the Vistula glaciation. The other experimental testing site, in the area of Elbląg, is located in the zone of a marginal Holocene delta of the Vistula River. As typical deposits of the delta of a large lowland river, they are a complex of interbedded silty, clayey and occasionally sandy soils. In this case, however, a typical characteristic of the soils tested is the presence of a considerable admixture of organic particles, frequently making it possible to classify these soils as organic silts.

Although soils from both experimental testing sites need to be considered as normally consolidated sensu stricte, the Pleistocene deposits in the surface zone were subjected to repeated changes in the level of ground waters, occurring in the Holocene. This fact led to the overconsolidation effect related to the drying and cementation of calcium carbonate in that zone.

2.2. Geotechnical Characteristic of Testing Sites

The subsoil at the testing site near Poznań was examined to the depth of 10 m. A typical profile is given in Fig. 1, and selected physical characteristics are presented in Table 1. Ground water is found at a depth of 2.2 m, with typical seasonal fluctuations of ± 0.5 m. The state of consistency of silty soils in the upper part is hard-plastic, below changing into plastic.

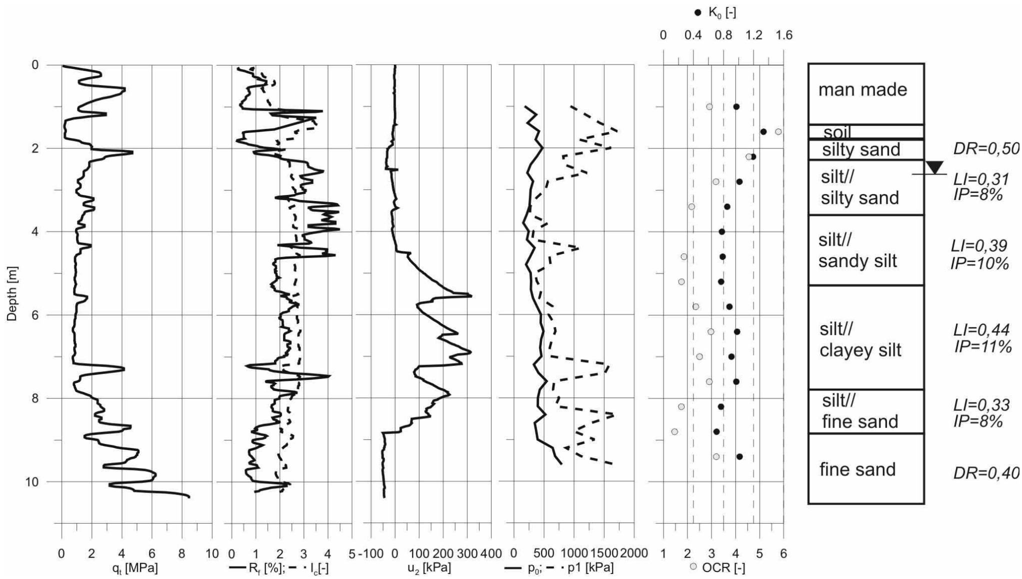

Fig. 1. Typical soil profile based on CPTU and DMT test results (Poznań test site), DR – relative density LI – liquidity index

The subsoil at the experimental testing site near Elbląg has a more complex geological structure, which is a consequence of two factors. Deposits from the delta of the Vistula River lie on older, strongly consolidated glacial and fluvioglacial sediments,

Table 1. Example of the results of a laboratory analysis of samples from the Poznań test site

Depth [m]	Sand content [%]	Silt content [%]	Clay content [%]	Natural moisture content [%]	Plasticity index IP [%]	Liquidity index LI [–]
2.2	60	31	9	20.4	11.2	0.32
2.5	62	29	9	17.5	6.8	0.20
3.2	64	27	9	19.5	9.5	0.39
4.6	60	31	9	21.2	10.8	0.42
5.8	59	32	9	21.8	11.1	0.46
6.9	38	50	12	19.6	9.8	0.40

and the character of deposition in the delta is connected with the presence of numerous layers, frequently exhibiting very different geotechnical properties. A typical geotechnical profile is presented in Fig. 2. The consistency of organic and silty soils is at the boundary of plastic and soft-plastic. Ground water is found at a depth of only 0.5 m, and its table is naturally correlated with changes in the water stage of the Vistula River.

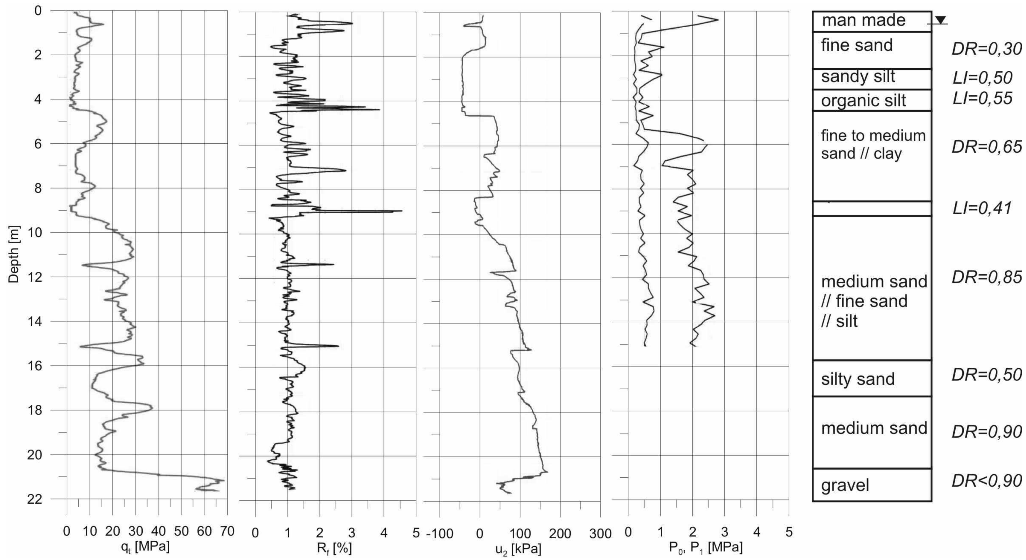

Fig. 2. Typical soil profile based on CPTU and DMT test results (Elbląg), DR – relative density LI – liquidity index

3. The Scope and Methods of Testing

In order to evaluate subsoil lithology at both testing sites, drillings were performed and samples for laboratory analyses were collected with a MOSTAP sampler, together with block samples from excavations. In the course of in-situ tests, CPTU static penetrations were performed with a Hyson 200 kN heavy static probe by A. P. van den Berg, as well as tests with a Marchetti dilatometer (DMT) and vane tests (VT). Vane testing was performed in a drill hole with an X-bit of 8 cm in height and 4 cm in width. Shearing was conducted at a constant velocity of 5°/min. CPTU tests were performed in accordance with the International Reference Test Procedure for Cone Penetration Testing TC-16 Committee ISSMGE (1997), and DMT was conducted in accordance with the Flat Dilatometer Test, a report to the ISSMGE Committee TC-16 (1999). Laboratory analyses covered the grain size distribution, physical properties and shear strength. Tests in a triaxial compression apparatus were conducted on samples at pre-consolidation according to the formula: CK_0U, $\sigma_1 = \sigma_{v0}$, $K_0 = 0.7$.

The second series of shear strength tests was performed on samples with a reconstructed structure. Samples were prepared in a Proctor apparatus, so as to model the embedding of the soils tested into an earthen structure. Shear strength parameters for those samples were determined in total stresses. Owing to the limited scope of this paper, testing results are presented for only one location: the one near Poznań.

4. Strength and Strain Parameters from in-situ Investigations

4.1. Stratigraphy and Overconsolidation Effect

In terms of their mechanical properties, alluvial deposits such as the soils tested are classified as the so-called transition soils (Kezdi 1969) or intermediate soils (Lunne et al 1997, Robertson 2009). In the currently applied classification of soils this group is located between fine soils and coarse-grained soils. A description of these soils in terms of strength is complicated, and in order to adopt an interpretation procedure for CPTU and DMT characteristics, the first step is to verify their position in the Soil Behaviour Type Chart system (SBT or SBTn – Robertson 2009). Such an approach is particularly important in the case of the soils tested, since irrespective of their genesis, these soils may exhibit the overconsolidation effect. This fact is significant for the evaluation of strength and strain parameters of these soils. An important characteristic differentiating the alluvial deposits near Elbląg from those near Poznań is the proportion of organic substance and strong interbeddings in the form of fine sands, found in the Elbląg subsoil.

The position of the soils in the SBTn chart perfectly reflects the effect of cyclic changes in ground water levels on the overconsolidation effect, which is more evident in the conventional SBT chart (Fig. 3). The I_C parameter, used in the classification of soils and based on this system, was obtained from the formula

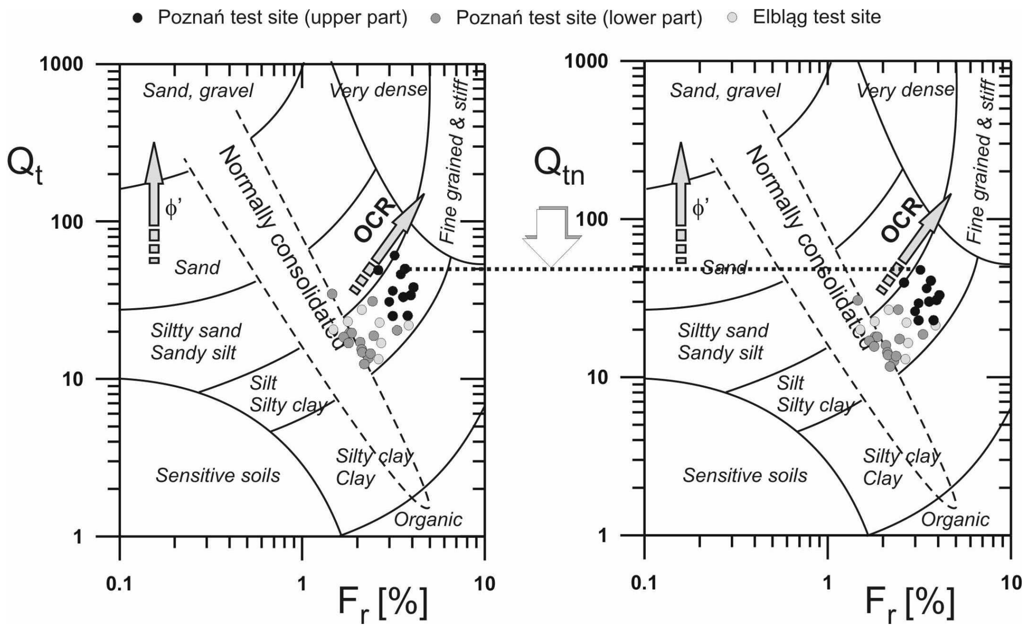

Fig. 3. Location of the investigated soils on SBT (left) and normalized SBTn (right) classification charts

$$I_C = \left[(3.47 - \log Q_{t1})^2 + (\log F_r + 1.22)^2\right]^{0.5} \tag{1}$$

where: $O_{t1} = (q_t - \sigma_{v0})/\sigma'_{v0}$, $F_r = [(f_s/(q_t - \sigma_{v0})]\ 100\%$, q_t – corrected cone resistance, f_s – sleeve friction, $\sigma_{v0}(\sigma'_{v0})$ – overburden stress (effective).

The overconsolidation effect of deposits is caused by both the action of the volume force of flow pressure and the formation of partial carbonate cementation. The zone affected by these factors is the surface section of subsoil, which extends to a depth of approx. 4.5 m at the Poznań site, and to a depth of 5.0 m at the Elbląg site. Below this zone, soils are normally consolidated, consistently with their genesis. Values of the overconsolidation ratio OCR were determined from CPTU and DMT with the formulas:

$$\mathrm{OCR} = 5.25 \ln Q_t - 14.97;\ \text{for soils with } I_p < 20\% \ \&\ Q_{t1} > 19 \text{ (Wierzbicki 2010)} \tag{2}$$

$$\mathrm{OCR} = 0.33 Q_{t1} \text{ (Mayne 1995)} \tag{3}$$

$$\mathrm{OCR} = 0.3 K_D^{1.17} \text{ (Lunneetal 1990)} \tag{4}$$

where: $K_D = (p_0 - u_0)/\sigma'_{v0}$, ($p_0$ – corrected A-pressure from DMT, u_0 – hydrostatic pressure), I_p plasticity index.

Figure 4, presenting the evaluation of OCR for silts from Poznań, shows that the application of the original formulas presented above does not lead to a definite evaluation of OCR from CPTU and DMT. The use of DMT in the evaluation of OCR for alluvial deposits, as shown by Viana Fonseca (2010), is more effective than CPTU.

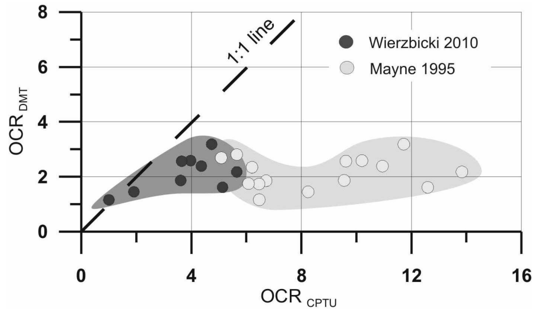

Fig. 4. Comparison of OCR evaluated from CPTU and DMT

However, if we correct the formula according to Wierzbicki (2010) to the form:

$$OCR = 1.2(5.25 \ln Q_{t1} - 14.97)^{0.43} \tag{5}$$

and apply the relationship given by Lunne for the evaluation of OCR from DMT parameters (Eq. 4), we obtain a high consistency of the evaluation of changes in the overconsolidation effect with depth. Figure 5 perfectly confirms variation in the position of the deposits on the SBT chart by Robertson, due to OCR of individual subsoil layers. The mean value of OCR in the overconsolidated zone is 2.1, whereas in the normally consolidated zone it is 1.0.

4.2. Shear Strength and Deformation Parameters of the Soils

4.2.1. Shear Strength Parameters

Shear strength of a subsoil of the fine-grained type in the geostatic state of stress is described by undrained shear strength S_u or Coulombian parameters expressed in effective stresses ϕ', c' (Lunne et al 1997, Senneset et al 1982, Sandven et al 1988).

The function that defines undrained shear strength in the geostatic state of stress for a layer of alluvial soil homogenous in terms of grain size distribution, may be described in the form:

$$s_u = f(\sigma_{v0}, \text{ LI}, \text{ OCR}, \theta) \tag{6}$$

where: LI – liquidity index, OCR – overconsolidation ratio, θ – coefficient of macrostructure of the soil.

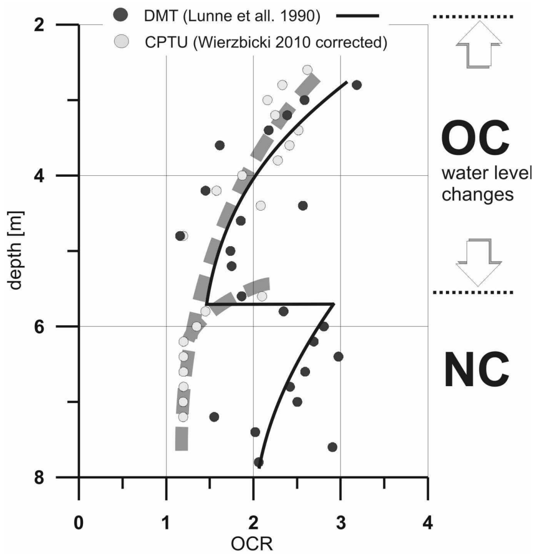

Fig. 5. Changes in OCR with depth for the Poznań test site

In the case of alluvial soils of organic origin, equation (6) has to be supplemented with a variable defining the content of organic particles. The function (Eq. 6) is dimensionally non-uniform. It may be transformed to a uniform dimensional form by the normalization of s_u, then:

$$\frac{s_u}{\sigma_{v0}} = f(\mathrm{LI}, \mathrm{OCR}, \theta) \tag{7}$$

To identify layer uniformity in the subsoil in terms of grain size distribution, we may use the I_C coefficient. This coefficient, unlike the R_f coefficient, highly effectively identifies the type of soils in the subsoils of Elbląg and Poznań (Fig.6).

Several highly significant conclusions for the evaluation of undrained shear strength of alluvial soils result from equation (6). A solution of function (6) has not been given to date. Generally, partial functions are determined, which represent the so-called local correlations and belong to a family of functions for different types of alluvial soils. The effect of structure on undrained shear strength is most frequently presented with a sensitivity index. This index may also be determined from CPTU with the function (Lunne et al 1997, Schnaid 2009, Robertson 2009):

$$S_t = \frac{N_s}{R_f} \tag{8}$$

N_S – constant, recommended average value of 7.5. For the soils tested, the S_t coefficient was 2.2 (OC) and 3.8 (NC) in Poznań, and 4.0 in Elbląg.

The values of this coefficient indicate that these soils are classified among soils of medium sensitivity.

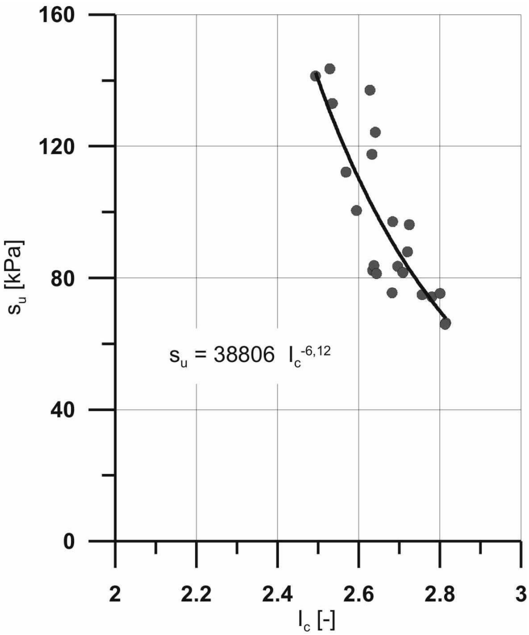

Fig. 6. Relationship between the I_c coefficient and undrained shear strength for the Poznań test site

A very important conclusion concerning potential in-situ testing methods may be drawn from function (6). The value of s_u is not determined directly from CPTU and DMT, and so the value obtained from those tests has to be referred through correction formulas to tests directly determining s_u, such as the vane test, or to laboratory analysis (Mayne et al 2009). Therefore appropriate N_k or N_{kt} coefficients need to be determined for CPTU. The quality of these coefficients will determine the quality of undrained shear strength determined in situ (Młynarek 2010).

In the case of the deposits tested, undrained shear strength was referred to the critical shear strength from VT – τ_u^{max}. In the solution of equation (7) for these soils the multiple linear regression method was applied, which yielded the following relationship:

$$s_u = 58.15 - 144.6\text{LI} + 34.74\text{OCR};\ R^2_{(OCR)} = 0.91. \tag{9}$$

The value of the multiple regression coefficient indicates that as much as 91% variation in undrained shear strength is related to the variation in OCR and the liquidity index. An analogous relationship for the deposits from Elbląg could not be determined. As a result of considerable interbeddings of organic soils in those deposits, the statistical estimate of this relationship was very low.

Partial functions resulting from equation (6) are of a significant practical importance, since they determine the relationship between undrained shear strength and changes in the liquidity index of deposits in the subsoil or OCR, or possibly the over-

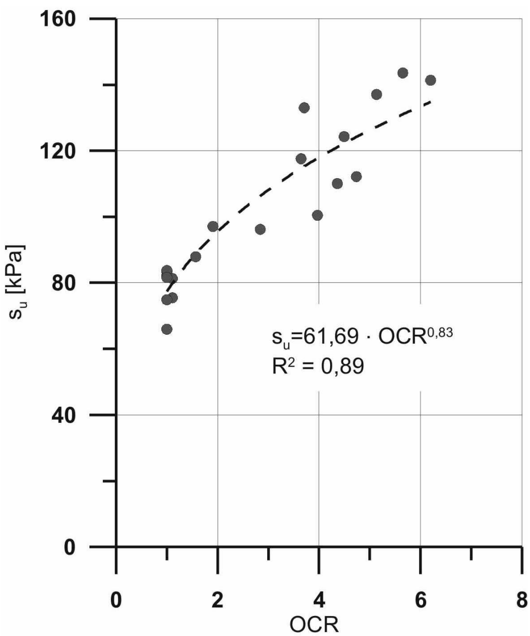

Fig. 7. Relationship between undrained shear strength s_u and liquidity index LI

burden stress σ_{v0} (Figs. 7, 8, 9). Changes in undrained shear strength with a change in the stress σ_{v0} show a linear trend, similarly as for fine-grained soils (Robertson 2009). The relationship between a change in s_u and the liquidity index, however, is described by an exponential function, approaching asymptotically the value of shear strength at the liquid limit. This value is close to 2 kPa for all fine-grained soils (Młynarek 1970, Horn 1964). Figure 7 shows that the trend of changes in s_u related to changes in the liquidity index is very similar and almost identical to changes from the vane test. In order to determine the trend of changes in s_u related to changes in the liquidity index and the consistency of these changes with changes in τ_{max} with the liquidity index, the values of undrained shear strength found in Fig. 7 were determined for the coefficient N_{kt} = 10 (Poznań) and N_{kt} = 17 (Elbląg). The consistency of trends makes it possible to determine the real value of N_{kt} for the two groups of deposits tested. If undrained shear strength is referred to strength from the vane test, then the values of N_{kt} are 7.5 for alluvial deposits from Poznań and 6.5 for alluvial deposits from Elbląg.

4.2.2. Constrained Deformation Modulus

Moduli describing the deformability of subsoil are determined from in-situ tests with empirical relationships. The relationship between the constrained modulus of deformation M_0 and parameters describing properties of alluvial subsoil is described by the same function which determines equation (6). The relationship between a change in the grain size distribution of soils and the modulus M_0 identifies the I_C coefficient

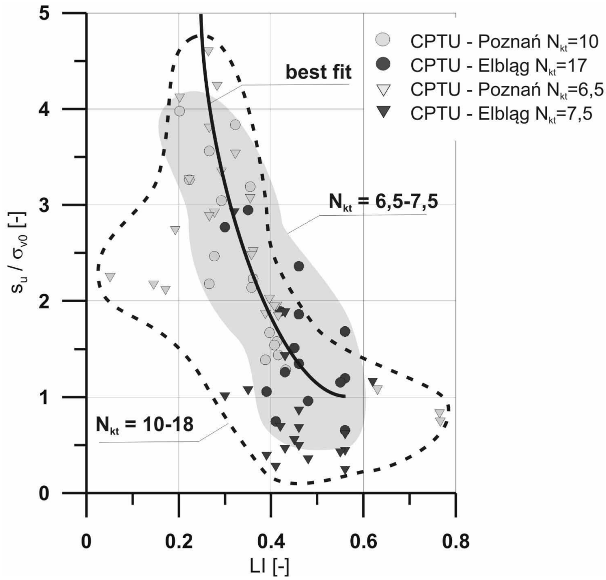

Fig. 8. Relationship between normalized undrained shear strength s_u and liquidity index LI for different N_{kt} values

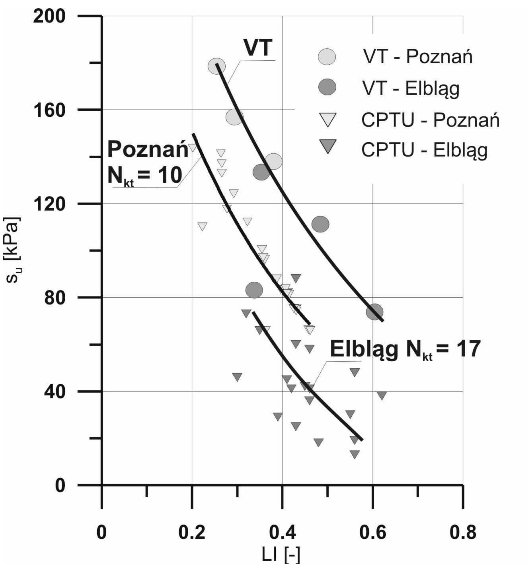

Fig. 9. Relationship between undrained shear strength s_u and overconsolidation ratio OCR for the Poznań test site

very reliably, similarly as for undrained shear strength (Fig. 10). A very good statistical evaluation of partial functions was obtained in the case of moduli determined from CPTU. DMT is a point test, and that is why a considerable variation in grain size and contents of organic particles in the Elbląg subsoil made it impossible to obtain a general correlation function. Therefore, the paper is focused on the analysis of the constrained moduli M_0 of silts from the Poznań test site, determined from CPTU results on the basis of Mayne's (1995) formula. Clear as the relationship between the M_0 modulus and the liquidity index may appear, the statistical estimate of this relationship is low (Fig. 11).

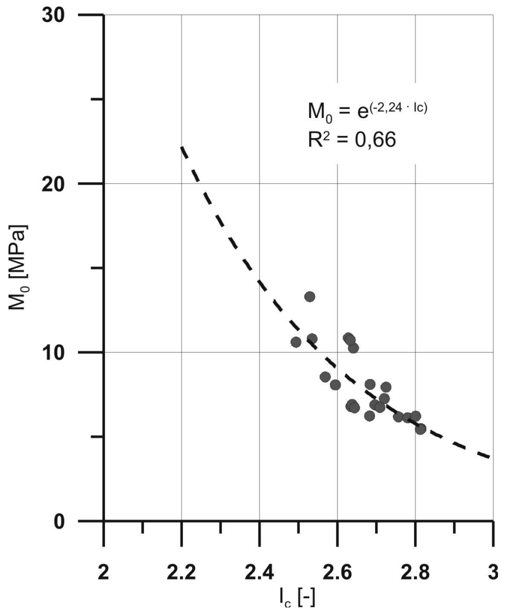

Fig. 10. Relationship between I_c coefficient and liquidity index LI for the Poznań test site

Moreover, relationships between the modulus M_0 and OCR, and the vertical stress σ_{v0} turned out to be highly significant for practical purposes. An analysis of this relationship shows that it needs to be considered as a joint function.

The abovementioned effect of these two variables on undrained shear strength turned out to be even stronger on the modulus M_0. This fact is very well illustrated in Fig. 12. In the normal consolidation zone, at a depth below 4.5 m, OCR is constant. In the overconsolidation zone, covering the surface zone, the modulus increases with an increase in OCR. An analogous relationship exists between the M_0 modulus and the preconsolidation pressure σ'_p (Fig. 13). The joint function, describing the relationship between the M_0 modulus and OCR, and LI, takes the form:

$$M_0 = 22.16 - 1.16\,\text{LI} - 0.19\,\text{OCR}, \quad R^2 = 0.98 \tag{10}$$

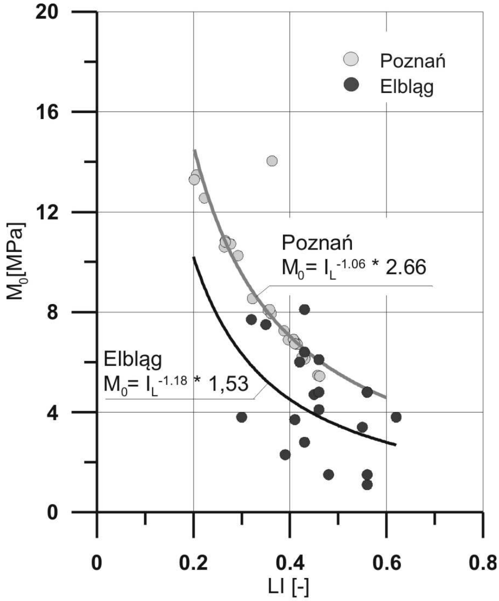

Fig. 11. Relationship between constrained modulus M_0 and liquidity index LI

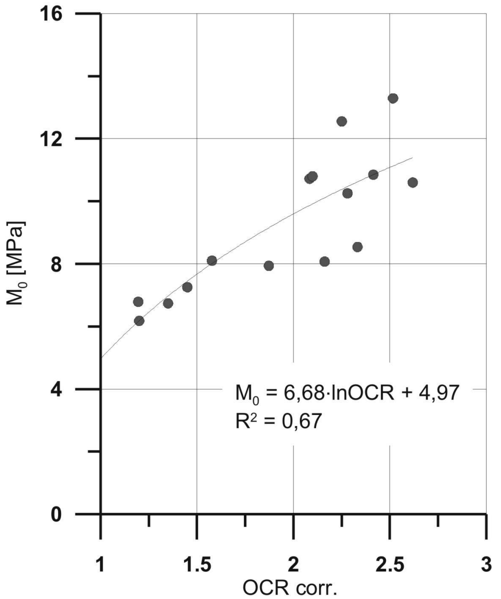

Fig. 12. Relationship between constrained modulus M_0 and overconsolidation ratio OCR for the Poznań test site

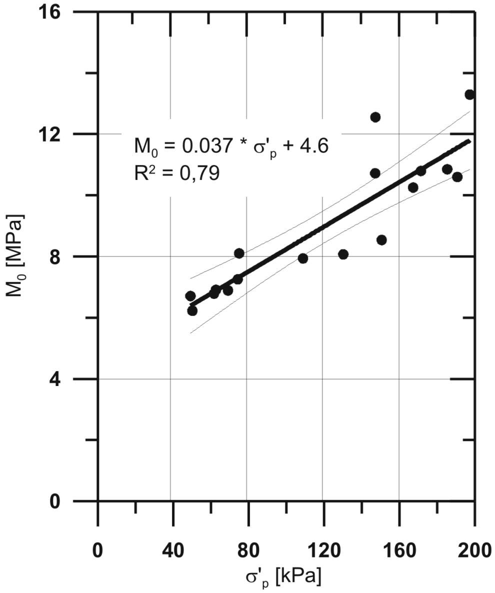

Fig. 13. Relationship between constrained modulus M_0 and preconsolidation pressure σ'_p for the Poznań test site

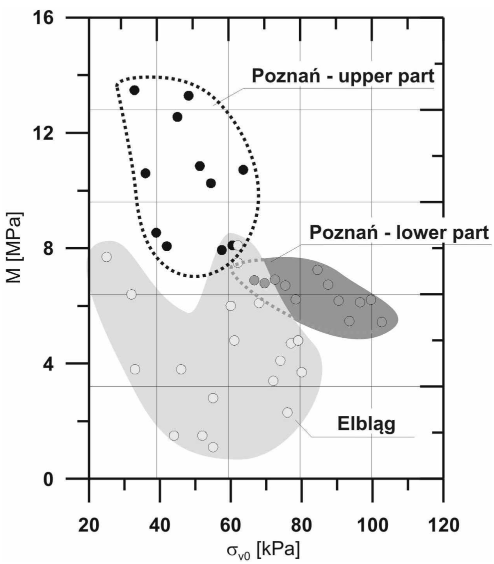

Fig. 14. Relationship between constrained modulus M and overburden pressure σ'_{v0}

Owing to the high variability in grain size distribution in the overconsolidation zone and the effect of OCR on the value of the constrained modulus of deformation in that zone, the effect of stresses σ'_{v0} on a change of the modulus does not have a functional relationship (Fig. 14). This conclusion is confirmed by statistical analysis, since a change in the M_0 modulus is caused in as much as 98% by variation in LI and OCR, and only in 1% by a change in σ_{v0}. This conclusion is of interest, since in homogenous deposits, which are classified as alluvial deposits, an increase in the value of the M_0 modulus with an increase in σ_{v0} is a commonly acknowledged fact. It results from function (10) that the evaluation of changes in the M_0 modulus for practical solutions requires the construction of a profile in the 1-D or 2-D system for each isolated subsoil layer (a model of subsoil rigidity – Młynarek et al 2007, Tumay et al 2011) with the use of basic relationships between the cone resistance q_c and M_0 modulus.

5. Alluvial Deposits as Material for Earthen Structures

The Proctor criterion is commonly applied in the evaluation of the suitability of soils for use in earthen structures. In comparison with the group of coarse-grained soils, two criteria are stressed in alluvial soils in terms of their suitability. One is the criterion of their compactibility, while the other is the determination of the most desirable shear strength parameters after the soil is embedded into an earthen structure. The shear strength of alluvial soils classified as silts is described by two parameters which are expressed in total stresses: cohesion c_u and internal friction angle ϕ_u. These parameters are understood as random variables, and are joint random variables (Benjamin & Cornell 1970, Młynarek et al 1988), since their variation is influenced by both moisture content w and density ρ_d (Fig. 15).

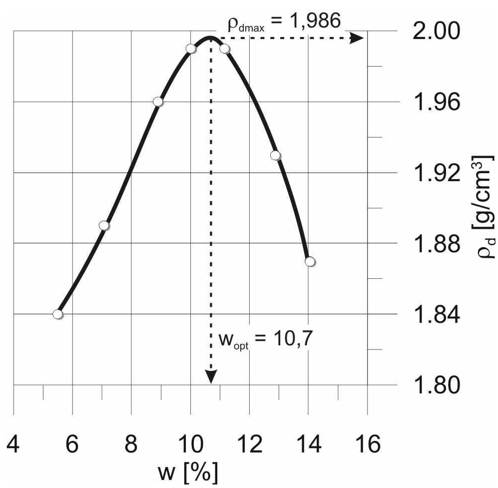

Fig. 15. Standard Proctor compaction test results for the Poznań test site

Thus the key questions are as follows: (i) what is the effect of independent variables, i.e. moisture content and density, on both strength parameters and (ii) is the optimal moisture content criterion from the Proctor test a definite criterion for the determination of their most desirable values? To confirm the effect of both variables on cohesion and internal friction angle we may use a diagram of soil phase composition (Kezdi 1969, Kezdi & Młynarek 1980). Variables ρ_d and w are replaced in this system by the components of the phase composition in the form:

$$S = \frac{\rho_d}{\rho_s} \cdot 100\%, \quad V = w \cdot \frac{\rho_d}{\rho_w} \cdot 100\%, \quad L = 100\% - (S + V) \tag{11}$$

where: S – the share of the skeleton, V – the share of water, L – the share of air, ρ_w – density of water, ρ_s – specific density of soil solids.

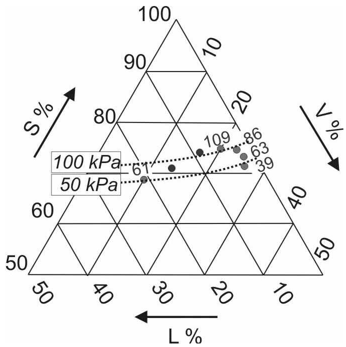

Fig. 16. Cohesion as a function of phase composition for silt from Poznań

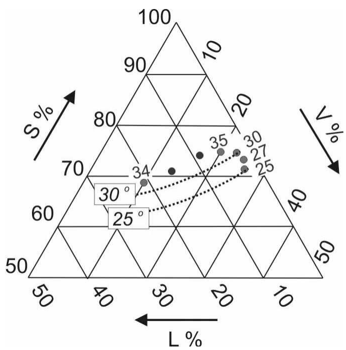

Fig. 17. Angle of internal friction as a function of phase composition for silt from Poznań

Figures 16 and 17 show that the effect of phase composition on cohesion and the angle of internal friction is clear. Isolines for cohesion and the angle of internal friction may be obtained for different phase compositions in a unit of soil volume, depending on the position of test points on the Proctor curve (Fig. 15). It results from the Proctor curve that the silt tested is a soil of good compactibility, since the curve has an evident point of inflexion at the optimal moisture content. However, this point does not correspond to the most desirable shear strength parameters (Figs. 18, 19). Thus, in order to obtain the most desirable shear strength parameters of the alluvial soil under analysis, it should be embedded into an earthen structure at a moisture content lower than the optimal level. It is an important statement from a practical point of view, confirming a conclusion presented in the literature on the subject (Wiłun 2000). It needs to be stressed that the cohesion values obtained above the optimal moisture content are very similar to undrained shear strength from CPTU.

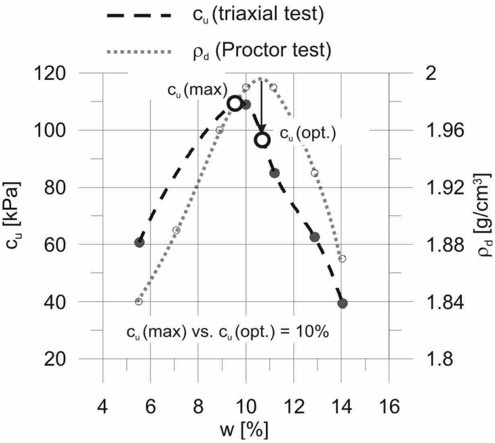

Fig. 18. Relationship between cohesion and water content for silt from Poznań

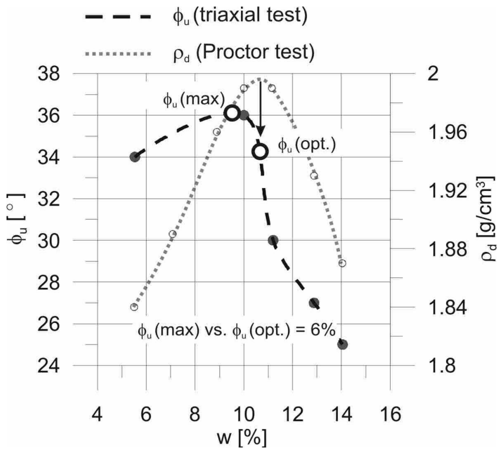

Fig. 19. Relationship between the angle of internal friction and water content for silt from Poznań

6. Conclusions

The tests conducted make it possible to formulate several important generalizations:

Alluvial deposits are characterized by high spatial variability in terms of their grain size distribution and consistency. This fact also results in a considerable spatial variation of strength and deformation parameters in the subsoil, despite a similar genesis. Each alluvial deposit should be considered as a separate interpretation problem for in-situ tests.

The overconsolidation effect, resulting from seasonal changes in ground water levels and cementation, has a highly significant effect on the mechanical parameters of deposits. This effect should be taken into consideration in the interpretation of shear strength parameters and constrained moduli of these soils. In alluvial deposits, where admixtures of organic particles are found, it is difficult to obtain generalized formulas for the determination of undrained shear strength and the constrained modulus of deformation on the basis of characteristics from CPTU or DMT. Among the deposits analyzed, this was the case of the subsoil from Elbląg. CPTU is a proper testing method for such a subsoil and a continuous recording of measured parameters, i.e. cone resistance, sleeve side friction and excess pore pressure, makes it possible to distinguish values described by mean values and then to construct 1D or 2D models of the subsoil on the basis of these parameters.

For an alluvial subsoil, in which silts with no organic particles are found, we may determine changes in undrained shear strength and the constrained modulus of deformation in the subsoil from CPTU penetration characteristics. It is necessary to correct the empirical coefficients in the formulas describing these relationships for fine-grained soils given in the literature.

Alluvial soils classified as silts are soils with good compactibility, meeting the criterion for their use in earthen structures. The most desirable shear strength parameters are not found at the optimal moisture content: in the case of the silt tested they were found at a moisture content below the optimal by approx. 1%. Above this point a rapid decrease in shear strength is observed.

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