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On the applicability of in situ soil probings to geological analyses

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Abstract

Examples of geoengineering methods (static and dynamic probings) that can be applied to analyses of geological environments are presented. The potential is shown by the results of the determination of the values of the soil-density index (I_D), the soil-behaviour index (I_c), the constrained modulus (M), the overconsolidation ratio (OCR) and their vertical changes. The values obtained for I_D and I_c facilitate the determination of layers with a specific character. This is demonstrated for several aeolian and glacial deposits in Poland. The application of static probings to the analyses of changes in OCR and M made it possible to identify several depositional phases and the effect of postdepositional processes. Usages of the probings can significantly contribute to the interpretation of palaeo-environments (e.g. in the context of geostatistical models), but the results obtained should be handled cautiously.

Keywords: dynamic penetration test, static penetration test, soil-density index, overconsolidation ratio

1. Introduction

In situ soil penetration with probing provides important supplementing data for analysis of the subsoil for foundations (e.g. Bażyński et al., 1999). It adds to routine analyses a quantitative element. Despite the introduction and continuous development of this research method in engineering sciences for over fifty years (Schnaid, 2009), its application is still relatively limited in earth science. It seems therefore justified to present here some case histories that show the potential advantages and limitations of using probings for soil testing.

1.1. Objectives

The main objective of the present contribution is to show how soil-penetration tests can be applied as useful research tools in analyses of the soil conditions. We focus here on the simplicity and rapid performance of probings and on the reliability of the values found for the parameters characterising the soil. The transition from qualitative characteristics to quantitative (parametric) characteristics of the investigated soil is desirable in order to eliminate a subjective evaluation of analytical results. It seems worthwhile to mention here as an example the method applied to describe the compaction of the grains in a non-lithified sediment (the so-called grain-compactness density) by means of a characteristic of the contacts between the grains (Gradziński et al., 1986). It is obviously a time-consuming method, which is also difficult to apply in an objective way; moreover, it may be performed only in well-exposed areas because the collection of undisturbed samples of unconsolidated deposits is difficult. Application of in situ probings can, to a considerable degree, eliminate the need to collect such samples, which is a considerable advantage.

The present contribution provides examples of how the depositional conditions are identified and how postdepositional processes have affected loose and cohesive deposits, based on the results of dynamic and static soil probings. It is indicated in which respect application of probings is convenient and – even more important – what is the most reliable method to determine a lithostratigraphy for sediments which do not differ clearly from each other in terms of their lithology. Finally, it is the intention to present general outlines for the application of probings for geological (mainly sedimentological) analyses.

2. Methodology and interpretation of the results

In situ soil probings have been applied for more than a century now. They were modified and improved, and the interpretations of the data have become more accurate (Tschuschke & Wierzbicki, 1998; Jamiolkowski et al., 2001; Frankowski, 2003; Młynarek & Wierzbicki, 2007). Probings consist in the penetration of a conical gauge into the subsoil in order to determine the resistance that the probe meets in the soil. Two main types of probing tests with probes can be distinguished, viz. dynamic and static tests. Several probing types may be distinguished: probings for dynamic tests drive the gauge cone into the soil by successive impulses, whereas static probings have a continuous thrust of 2 cm s^{-1}. On the basis of the results thus obtained, several physico-mechanical parameters of soils are calculated, e.g. the density index (I_D), the constrained modulus (M), and the internal friction angle (φ) (Pisarczyk, 2001; Młynarek, 2004).

2.1. Dynamic probing

The density index of soils can be determined on the basis of light dynamic penetration probing. This type of probing determines the number of blows (N_{10}) needed for a 10-kg hammer, falling from a height of 0.5 m on an anvil that is constructed on a rod connected with the probe to make the probe penetrate the soil by 10 cm (Fig. 1). The number of blows is then converted (according to PN-2002/B-04452) into the value of the soil density index (I_D) based on the formula:

$$I_D = 0.429 \log N_{10} + 0.071 \qquad \text{(Eq. 1)}$$

In standard geotechnical analyses of the subsoil, probing is completed when the number of blows is larger than 30 over a section of 20–30 cm in the soil profile. This is equivalent to the value for compacted soils ($I_D > 0.67$, according to PN-81/B-03020).

It should be mentioned here that the probings in the analyses detailed underneath were, in contrast to the approach mentioned above, performed to an assumed depth, with the number of blows not being limited to the level specified by the standard, even it was over 70. This procedure enabled a more detailed analysis than possible with the standard procedure, which was necessary because the present study required a higher accuracy of the measurements than needed for a normal geotechnical test.

2.2. Static probing

Static probing, better known as Cone Penetration Testing (CPT, CPTU), is a geotechnical analysis consisting of static, vertical penetration of a measuring gauge in the subsoil (e.g. Sanglerat, 1972; Młynarek, 1979; Lunne et al., 1997; Schnaid, 2009). The standards for the application of this in situ test, which is one of the most

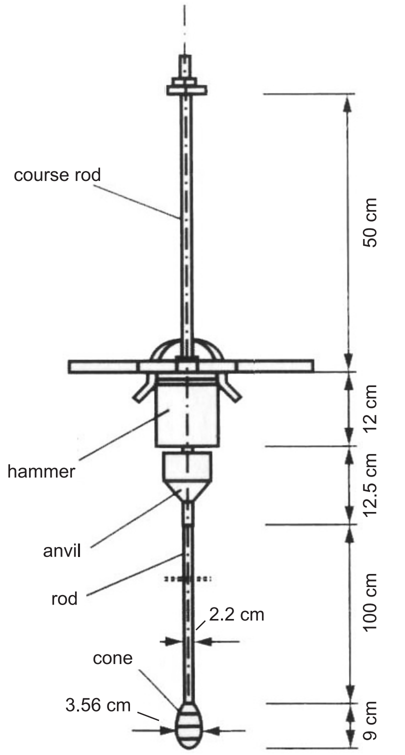

Fig. 1. Scheme of a dynamic penetration light probe (DPL).

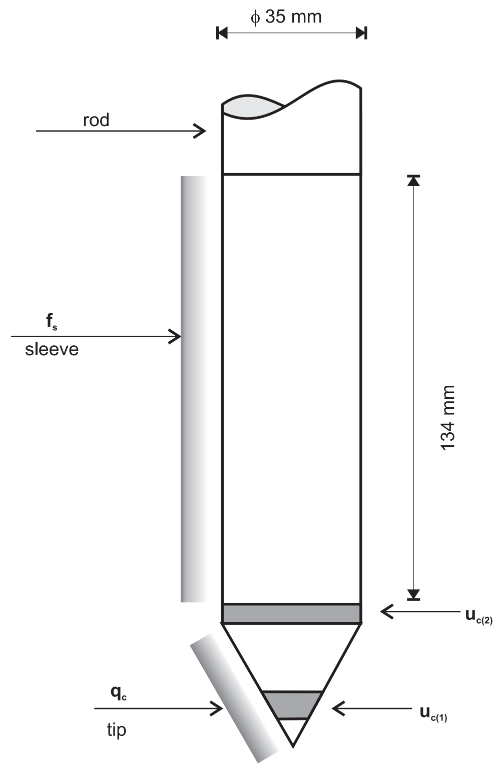

Fig. 2. Scheme of a CPTU cone.

commonly applied geotechnical tests, are specified in the TC-16 manual (ISSMGE, 1999) and in the European Standard EN ISO 22476-1.

In the course of the CPT-type probing, the cone resistance (q_c) and sleeve friction (f_s) are recorded (Fig. 2). Testing the CPTU method is supplemented during the test with measurement of the pore-water pressure (u_2). In the case of the CPTU method, the resistance and friction parameters are corrected, which is required because of the design of the measuring system, that is susceptible to the effect of the excess pore-water pressure in the soil that is induced during the penetration (Lunne et al., 1997). As a result of this correction, a corrected cone resistance (q_t) and a corrected friction at the sleeve friction (f_t) must be used. The parameter f_t is corrected sporadically only, because the pore pressure at the sleeve is usually not known. The friction ratio (R_f) is determined on the basis of parameters q_c and f_s after correction, i.e. q_t and f_t:

$$R_f = \frac{f_t}{q_t} 100\% \qquad \text{(Eq. 2)}$$

The use of additional geological information about the analysed subsoil, such as its hydrostatic pressure and the bulk density of the soil makes it possible to determine some important normalised parameters, such as the normalized resistance of the cone (Q_t) and the normalized pore pressure parameter (B_q) (for details, see Lunne et al., 1997), parameters characterising the strength and deformation properties of the soil under investigation.

The results of static probing are used for a first interpretation of the geotechnical properties of the subsoil (Lunne et al., 1997; Sikora, 2006; Mayne, 2007). Analyses conducted by Młynarek et al. (2008), and Wierzbicki & Stefaniak (2009) indicate that it is necessary for the purpose to describe the penetration process using a complex model, taking into consideration among other aspects the state of stress in the subsoil, the condition of the soil and its textural and structural characteristics. In order distinguish compartments of specific lithological properties in the subsoil (i.e., homogeneous parts of the profile with characteristics differing from those of the adjacent material), one

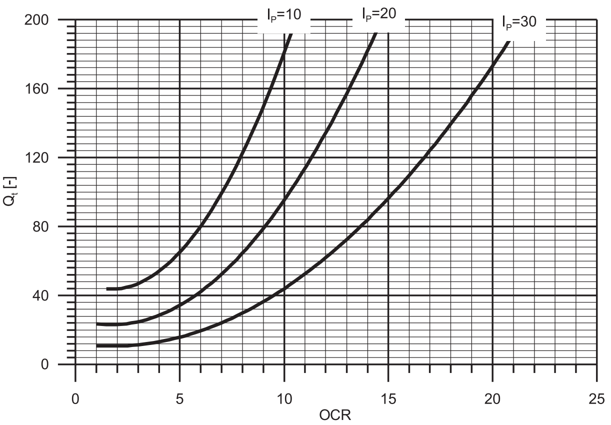

Fig. 3. Correlation of Q_t with OCR showing the influence of I_p (in %) for cohesive soils (from Wierzbicki, 2010).

may either use the values obtained directly by CPTU probing (q_t, f_s, u_c), or interpret the values of geotechnical parameters such as the density index (I_D) (Eq. 3), the constrained modulus (M) (Eq. 4) or the overconsolidation ratio (OCR) (Fig. 3). The complicated character of static cone penetration makes it in practice impossible, however, to develop generally valid relationships between the above-mentioned geotechnical parameters on the basis of probing results. The present study uses the latter approach, which is – according to our experience – the most suitable for soils in Poland, because they can be estimated in detail due to local geoengineering conditions.

The density index is calculated according to the formula (Baldi et al., 1986):

$$I_D = \frac{1}{C_2} ln \left[\frac{q_c}{C_0 \left(\sigma'_{v0} \right)^{C_1}} \right] \qquad \text{(Eq. 3)}$$

where

C_0, C_1 and C_2 are soil constants (e.g. for fluvial and quartz sand, C_0 = 17.68, C_1 = 0.50, and C_2 = 2.31); σ'_{v0} = the effective vertical stress [kPa].

The constrained modulus is calculated according to the formula (Senneset et al., 1989):

$$M = \alpha \ (q_t - \sigma'_{v0}) \qquad \text{(Eq. 4)}$$

where α = a soil-type-dependent coefficient, ranging from 4 (non-cohesive soils) to 8.25 (cohesive soils).

The application of the values of the geotechnical parameters to the geological interpretation of the subsoil makes it possible, although requiring more detailed analyses, to link the results of static probing with some features of the investigated deposits, such as different ages and depositional conditions, as well as postdepositional processes (Wierzbicki, 2009).

As mentioned above, the traditional CPTU parameter used to assess the lithological variation a profile is the friction ratio (R_f) (Lunne et al., 1997). Since the f_s measurements cannot always be replicated (Lunne 2010) and because the correlation with the drainage conditions of the soil is not always clear, u_2 should be investigated simultaneously. Determination of these parameters makes it possible, first of all, to recognise layers in the subsoil that differ with respect to their soil type. Numerous classification diagrams are used for the purpose; their advantages and drawbacks have been discussed by, among others, Młynarek et al. (1997) and Been et al. (2010). Long-term experience in the application of classification diagrams has led in the past few years to the introduction of a new parameter that characterises the type of soil in CPTU, viz. the soil-behaviour index (I_c) (Robertson, 2009), which can be calculated according to the formula:

$$I_c = [(3.47 - \log Q_t)^2 + (\log R_f + 1.22)^2]^{0.5} \qquad \text{(Eq. 5)}$$

This parameter seems in many respects to reflect the subsoil lithology more accurately than the traditionally applied friction ratio (R_f) (Been et al., 2010).

2.3. Correlation of probing results

The best methods to determine the geological structure of the subsoil, up to a depth of around a dozen metres, include the exposure of the material, performed rather rarely, and drillings. The latter provide information on the geological structure only at the drilling site, however, so that the geological structure must be interpreted on the basis of drillings and correlation of previously documented layers. Due to the high cost of drillings and their long duration, in situ soil probings have become increasingly common, particularly in engineering geology and geotechnics.

It must be emphasized in this context, however, that unprocessed probing results, leaving space for different interpretations of the interpretation diagrams from both Polish and European standards – particularly in relation to static probings – frequently do not reflect the actual geological structure of the subsoil. It is therefore common practice to drill at least one borehole, which is used as a reference point for the calibration of local probing results. With such a reference point for correlations, probings become useful and their interpretations then turn out to be more reliable and precise.

3. Examples of the application of in situ soil probings in geological analyses

The present contribution focuses on the application of the results from dynamic and static soil probings for three purposes: (1) evaluation of the suitability of these techniques for the recognition of boundaries between sedimentary layers with different lithologies, (2) reconstruction of the variations in the depositional conditions of the sediments, and (3) identification of the characteristics of postdepositional changes in the sediments. The case histories chosen here concern investigations performed lately by the present authors in the Warta-Noteć interfluvial region (WNI), the Kampinos National Park (KNP), the Słowiński National Park (SNP) and the Parsęta Lobe (PL) (Fig. 4).

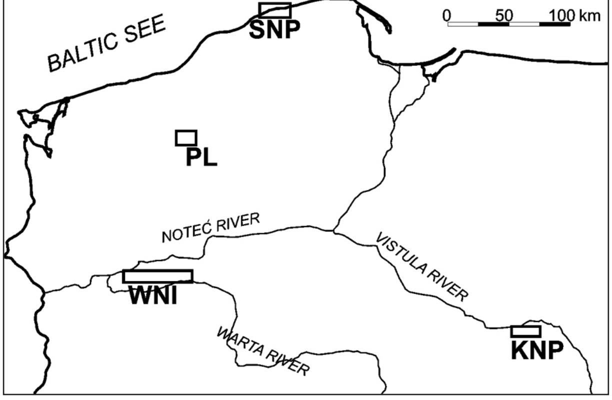

Fig. 4. Locations of the study areas.

3.1. Determination of lithogenetic variation in subsoil

A first example regarding the application of (dynamic) probings concerns the area of inland dune fields in the KNP and WNI; the probings were performed in terraces of the Wisła, Warta and Noteć rivers. Because the dunes here were created – at the end of the Pleistocene – by the deflation of extensive surfaces of terrace sands, the lithology of the dune sands is identical to that of the top of the dune subsoil. The identification of the boundary between the aeolian deposits and the deeper subsoil of fluvioglacial origin is therefore commonly difficult to establish. Such a transition is illustrated in Figure 5, which gives – on the basis of three dynamic probings – an impression of the change of the density index I_D at the boundary between these sediments in the KNP. Tests of the dunes and aeolian sand covers of limited thickness made it possible to identify the top of the terrace deposits distinctly. A similar picture of the change in I_D between aeolian sediments and periglacial fluvial deposits in the WNI has also been docu-

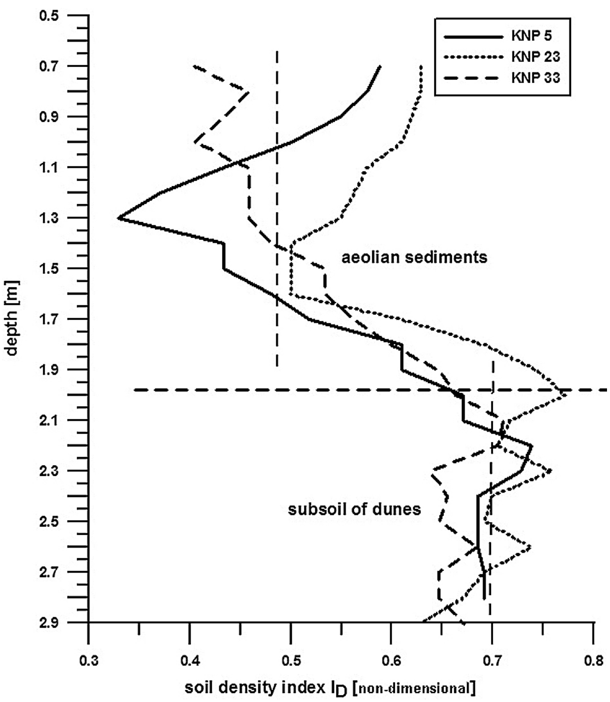

Fig. 5. Rapid increase in the relative density index (I_D) in surficial layers at the boundary between aeolian sediments (dunes) and their immediate substratum (Wisła River terrace sands), as commonly present in the KNP area.

mented thanks to CPT static probing (Radaszewski & Wierzbicki, 2007).

A second example of the application of CPTU probings concerns the boundary between two cohesive layers, viz. glacial tills of the Pomeranian and Poznań phases near Barwice (PL). The boundary was found on the basis of a change in the soil-behaviour index (I_C). Both a literature survey and field investigations (Maksiak & Mróz, 1978; Dobracka & Pisarska, 2002) indicate that the various tills are here only occasionally separated from glaciofluvial deposits. Over large areas the stratigraphic subdivisions may be performed only by analogy, e.g. on the basis of the thickness of a clay deposit of known age. In such situations, additional data (parameter I_c) enable to interpret the stratigraphy (see Fig. 6). The transition in this profile from one stratigraphic unit to another is indicated by a change in I_C. The potential applications of such static probings to the genetic interpretation of glacilacustrine deposits, supported by the use of statistical data analysis, have been presented in more detail by Wierzbicki et al. (2007).

3.2. Reconstruction of the variations in depositional conditions

Another example of the application of (dynamic DPL) probings, used to interpret the recorded changes in palaeo-environmental conditions possibly affecting the depositional history, is the analysis of the density index (I_D) in dune sands and cover sands. The case study presented here was conducted in three areas, viz. the KNP and WNI (inland dune fields) and

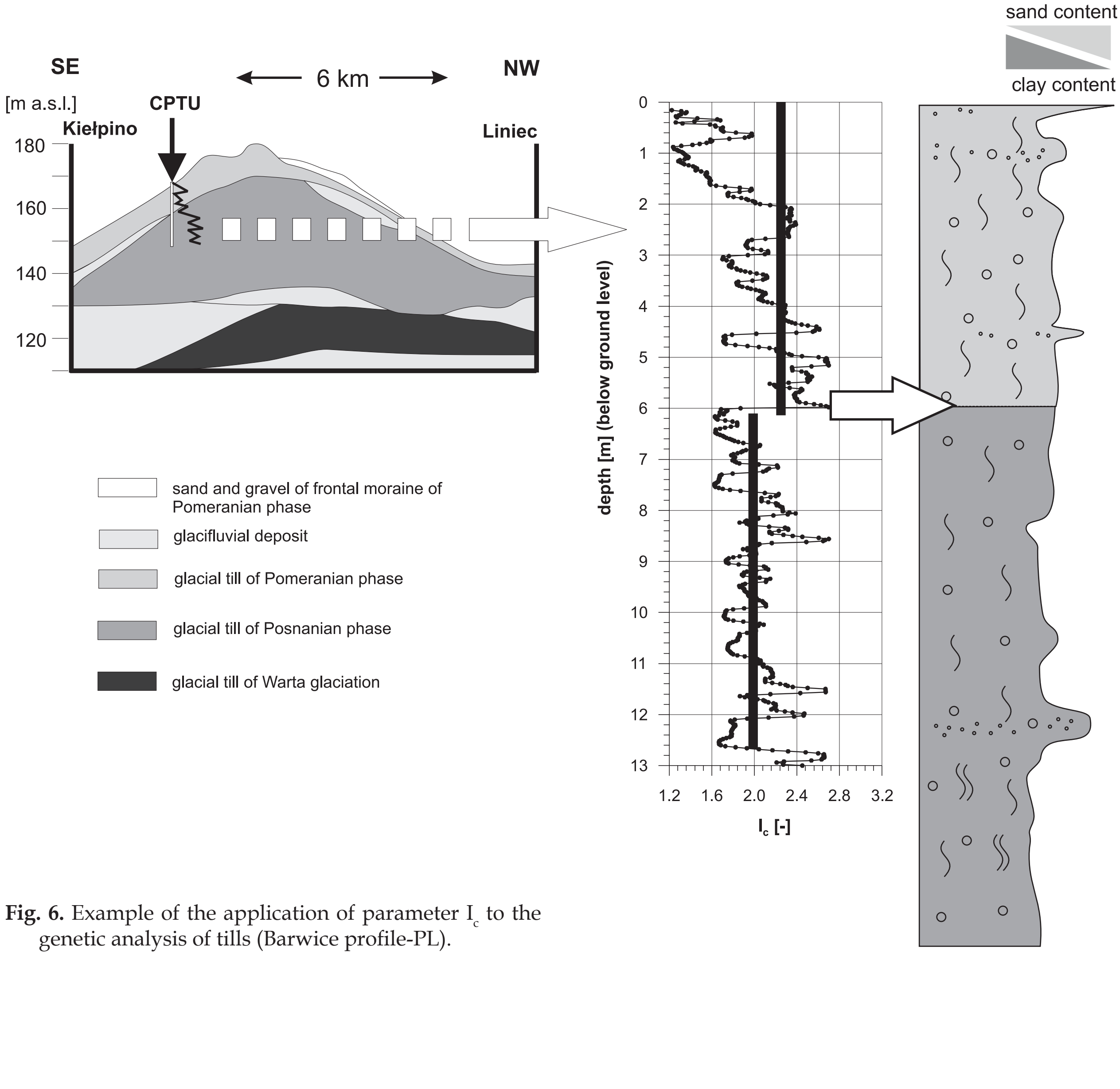

Fig. 6. Example of the application of parameter I_c to the genetic analysis of tills (Barwice profile-PL).

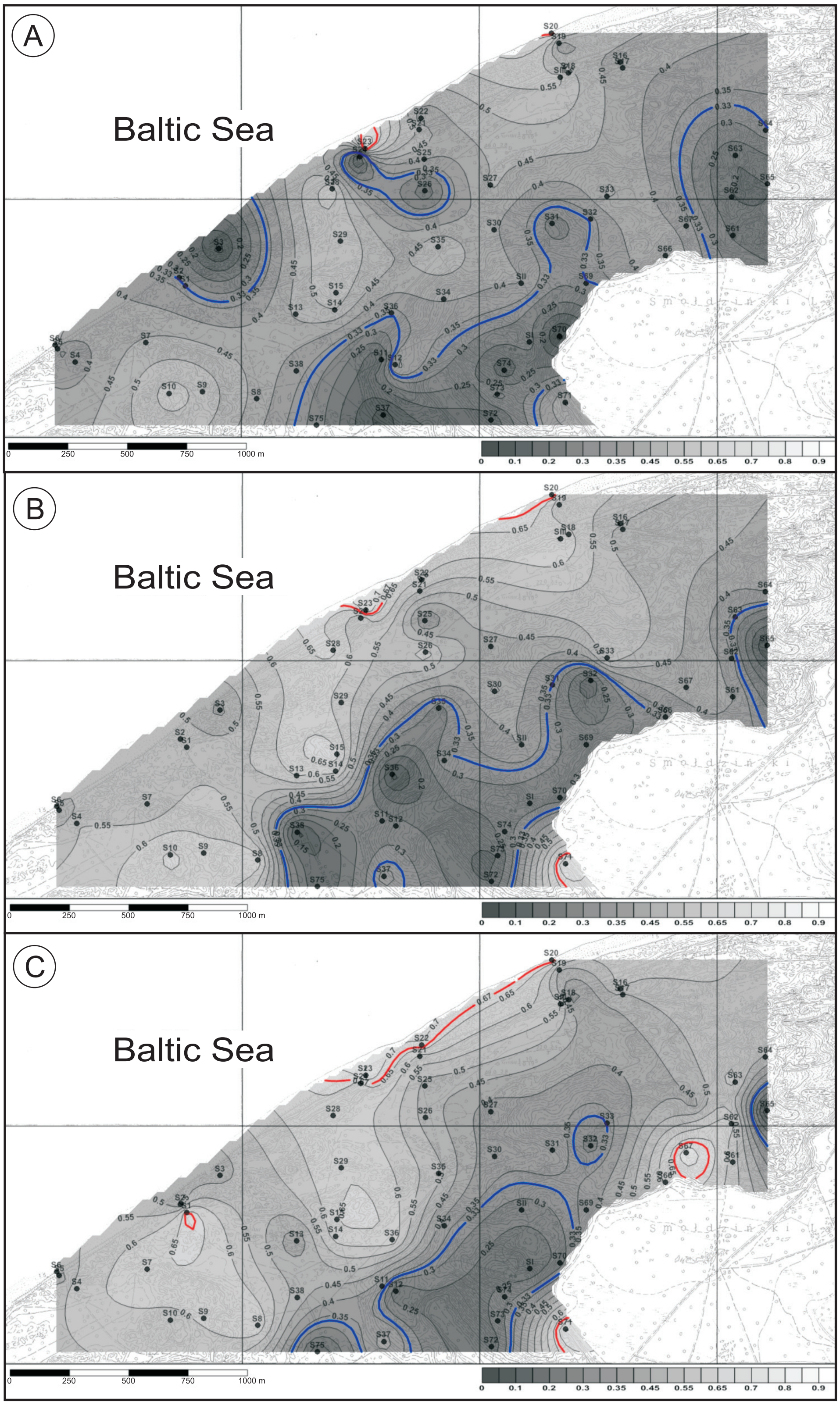

Fig. 7. Characteristics of the compaction of the subsoil in the Słowiński National Park west of Lake Łebsko, in the vicinity of the lighthouse at Czołpino, at different depths. Dots mark probing sites; the red isoline denotes the value I_D = 0.67 (the boundary between the medium-compacted and compacted states). The blue isoline denotes the value I_D = 0.33 (the boundary between loose and medium-compacted states).
A – 1 m below ground level; **B** – 2 m below ground level; **C** – 3 m below ground level.

the SNP (modern active coastal dunes). These deposits are composed mainly of fine- and medium-grained (M_z = 0.2-0.3 mm), very well sorted sands ($U = D_{60}/D_{10}$ = 1.4–2.2) of which the grains are subrounded and rounded (poorly rounded α = 35–50%, medium rounded β = 35–50%, and well rounded γ = 4–11%, according to the classification proposed by Krygowski, 1964). They do not show stratification (they have a massive structure), but in spite of their apparent lithological homogeneity, the density index shows large variations. In the investigated areas of the KNP, WNI and SNP, which have a total surface area of approx. 20 km^2, over 280 shallow probings (i.e. with a depth of max. 4 m below ground level) and 14 deep probings (up to a depth of 7 m) were performed, with a total length of over 1 km. The locations of the probes for dynamic penetration tests (DPL) were determined by (1) the requirement to plot compaction maps for the deposits at a depth of 1, 2 and 3 m (examples of such maps concerning the surroundings of a lighthouse in Czołpino in the SNP is presented in Figure 7); and (2) the need to document the variation, assumed on the basis of literature (e.g. Bagnold, 1941; Borówka, 1980), in the density index of aeolian sands on both the windward and leeward slopes of dunes; the analyses fully confirmed and – what is a step forward – also reliably showed that the values that were assumed on the basis of literature, particularly in inland dune fields of the KNP and WNI areas were correct) (see Fig. 8).

Since the deposits had almost identical structural and textural characteristics, the lateral and vertical variations in I_D values shown in Figure 7 are probably influenced by the local conditions, both during and after their deposition; this, unfortunately, disturbs the clarity of the picture. The responsible local conditions must have included, particularly for the SNP dunes, the wind directions and variations in subsoil moisture content and humidity, dependent of whether the dune slopes were directed northwards (seawards), or towards the south. The effects of these factors were superimposed on the standard mechanisms of aeolian transport, i.e. the compaction of the aerodynamic stream saturated with blown sand on the windward side of dunes and the gravitational transport of grains on their leeward slopes.

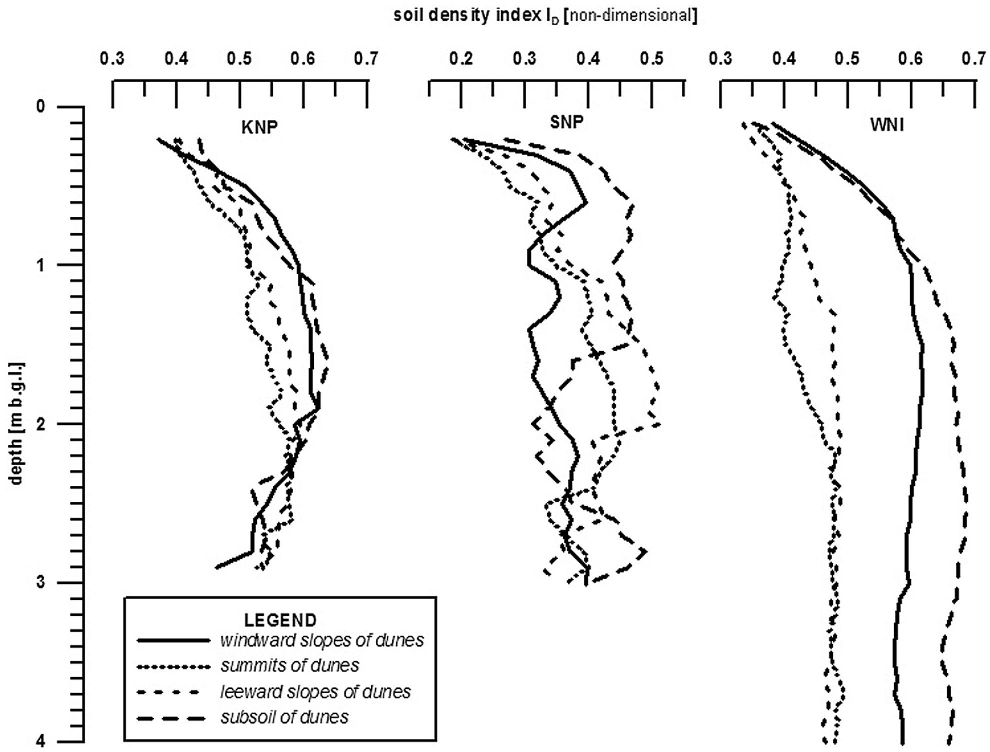

Fig. 8. Generalised variations in the density index of the aeolian sands (calculated on the basis of results of dynamic probings with a DPL probe) from the KNP, WNI, and SNP, resulting from dune morphology.

The combined effect of these phenomena is evident particularly in the near-surface layers of aeolian sands. It disappears with depth, as found most clearly in sands of modern active dunes in the SNP. The variation in the density index as a result of dune morphology in the inland dune fields of the WNI is closest to theory, as the assumed, theoretical situation is still found at a depth of 4 m.

The recorded I_D values suggest the following.

(1) The density of a deposit increases with time as a result of postdepositional processes. The loosest aeolian sands occur in the present-day active dunes of the Słowiński National Park, while the dunes of inland fields in the KNP and WNI, which are similar in age (forming since the end of the Pleistocene, up to the middle Atlantic: Radaszewski, 2003), exhibit densities that are mutually identical, but distinctly higher than that of the dunes in the SNP.

(2) The occurrence of zones of more or less compacted sand in the dunes, which are exceptionally homogeneous in grain size, may be explained primarily by fluctuations in the intensity of the aeolian transport, which may be high in certain periods (zones of less compacted sand) or low (more compacted zones). This thesis might ultimately be confirmed by an accurate dating of aeolian–sand successions, preferably by OSL, which will be undertaken in the future.

3.3. Characteristics of postdepositional changes

Postdepositional (early–diagenetic) changes leading to the consolidation or even overconsolidation of the subsoil determine the strength properties of a soil fundamentally. They may therefore be reflected in the results of geotechnical soil analyses. The possibility to use static probings for the identification of the effect of postdepositional processes on sediments was shown by Wierzbicki (2010). Despite of other formulas allowing to calculate the overconsolidation rate (e.g. Mayne, 1995), the used solutions proposed by Wierzbicki (2010) on the basis of oedometer tests gave the most accurate estimates for glacial tills. Additionally the research procedures developed by Wierzbicki make it possible to identify the vertical changes in the overconsolidation ratio (OCR) and to facilitate the evaluation of subsoil stratigraphy based on premises resulting from the effect of postdepositional changes on the deposit. In that case the OCR values reflect not only the simple loading/unloading process but several other postdepositional changes as well (as mentioned by Jamiolkowski et al., 1985). It should be emphasized that the OCR should reflect the overconsolidation effect on the subsoil Wierzbicki (2010).

The complex nature of geological processes does not allow – without additional geological analyses – to evaluate the type of a specific process definitely, but can indicate only relative changes in a profile. This is in itself already a valuable premise, supporting the analysis of subsoil stratigraphy. An example of an applied OCR analysis regards the above-mentioned profile of tills from Barwice, where OCR values were derived using the soil-behaviour models developed for tills by Wierzbicki (2010) on the basis of a theoretical analysis and correlations with laboratory-derived OCR values using the methods of Casagrande (1936) and Janbu et al. (1981). Some of the solutions of these models are presented in Figure 3. Irrespective of the recognised lithological units, changes in OCR values occur in this profile (Fig. 9). The scattered character of the calculated OCR values corresponds well with the scattering of other geotechnical parameters (such as the constrained modulus), which emphasizes the nature of the models used for OCR calculations, which are proper only in their statistical meaning.

Based on observations by Locat et al. (2003), at least two or even three fragments in this profile can be recognized as having been affected by subsoil overloading at different moments. The characteristic 'cut-off' of the upper parts of the OCR profile may indicate erosion of part of the overlying layer before the deposition of younger tills. The recognized layers are also detectable by analysis of the subsoil rigidity. The mean values of constrained moduli determined on the basis of CPTU clearly indicate

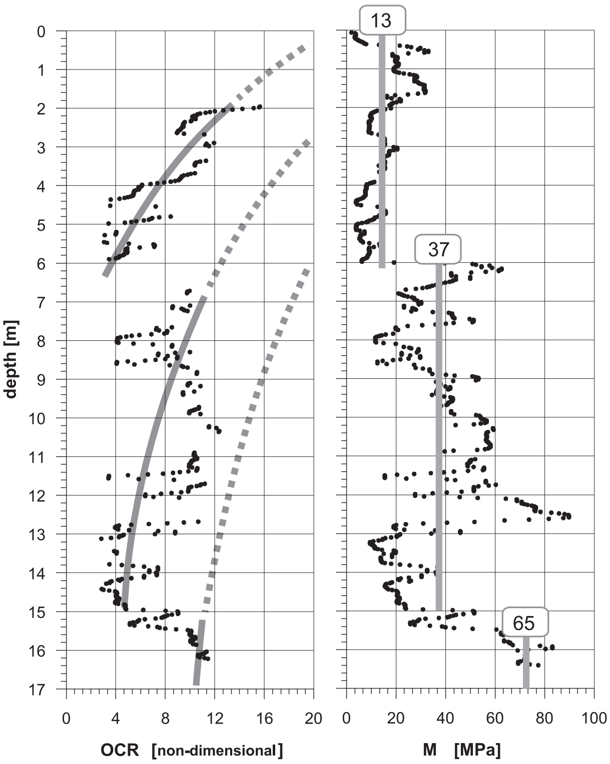

Fig. 9. OCR profiles corresponding to the average values of M, as calculated for the till at the Barwice (PL) test site.

three parts in the profile that differ in terms of consolidation. The OCR changes in the tills might also be explained by differences in the depositional conditions, as for a melt-out till and a lodgment till.

Another important problem connected with the analysis of the effect of postdepositional processes is the observation of elevated OCR values in normally consolidated glaciolacustrine deposits (e.g. Zawrzykraj, 2006). As shown by Wierzbicki (2010), the effect of overconsolidation in glaciolacustrine deposits needs in this case be connected with the effect of processes not related with overloading or erosion of the overlying layer, but with the influence of the water-flow pressure and drying of the deposit.

4. Conclusions

In situ soil probing, of which the potential applicability to traditional geological analyses is recently assessed, has several advantages. These include the quickly obtained analytical results, a considerably reduced requirement for sampling and laboratory analyses, and quantitative parameters of the soils under study. The main advantage of this method is objectivity of the analysis of input data.

Apart from these advantages, there are also some limitations. The main problem is not due to the probings themselves, but with their interpretations, as these may be manifold. Moreover, geotechnical parameters calculated on the basis of probing results, including, for instance, I_D and OCR, depend on many factors. For example, the variation in the soil-density index I_D, indicates even in thin layers a high sensitivity of this parameter as it depends on internal (structure, texture) and external (time, moisture content, loading by the overlying layer, etc.) factors. In the case of OCR values, it is necessary to identify the basic physical properties of the deposit by collecting reference samples. When analysing the values of this parameter, it is necessary to consider the complexity of the overconsolidation effect of the subsoil and the high number of factors that influence this effect (Wierzbicki, 2010). It emphasized the limited application of the usage of R_f values as single indicators of the subsoil composition.

On the other hand, the present authors' experience in strongly and moderately overconsolidated soils shows a better applicability of the sleeve friction (f_s) than reported by Lunne (2010) for soft clays from the Onsoy area (Norway). This is probably due to two factors: the use of equipment from only two manufactures, and the higher horizontal-stress component in overconsolidated soils, which shift the range of f_s measurements from 20 kPa to almost 200 kPa (and the high stiffness value of the subsoil reduces the tip penetration on the sleeve friction). Wierzbicki (2010) has shown also the statistically important correlation between normalized f_s measurements and the changes in the values of the coefficient of the earth pressure *at rest*, corresponding to simple unloading.

In terms of environmental geology, these facts seem to limit the applicability of dynamic and static probings in non-cohesive soils to local tests, in which certain characteristics may be assumed to be constant. Probings documenting the compaction of aeolian deposits need to be treated rather as supplementary analyses. At a larger scale, the variations in soil density may be so significant, they may vary so chaotically, and they may be interpreted in so many different ways that I_D becomes a less suitable parameter for analyses.

The applicability of static probings in cohesive soils is different. These soils exhibit regionally more identical lithological characteristics, thanks to which probing results also will be fairly similar, thus facilitating geological analyses at a larger scale.

An additional advantage of the use of probings, particularly static probings, is connected with the possibility to perform statistical analyses of the data characterising the subsoil. Particularly promising results were obtained with cluster analysis, both at the local scale of a single profile and in geological models covering an area of many square kilometres.

Considering the advantages and limitations of the application of probings, irrespective of their type, they seem to be a good supplementary tool for local sedimentological analyses.

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References

Bagnold, R.A., 1941. *The physics of blown sand and desert dunes* (1973 ed.). John Wiley & Sons, New York, 255 pp.

Baldi, G., Bellotti, R., Ghionna, V., Jamiolkowski, M., Marchetti, S. & Pasqualini, E., 1986. Flat dilatometer tests in calibration chambers. *Proceedings of In Situ '86* (ASCE Special Conference on "Use of in situ tests in geotechnical engineering", Virginia Tech, Blacksburg, VA). American Society of Civil Engineers Geotechnical Special Publication 6, 431–446.

Bażyński, J., Drągowski, A., Frankowski, Z., Kaczyński, R., Rybicki, S. & Wysokiński, L., 1999. *Zasady sporządzania dokumentacji geologiczno–inżynierskich* [Engineering geological documentation – Principles of preparation]. Państwowy Instytut Geologiczny, Warszawa, 184 pp.

Been, K., Quiñonez, A. & Sancio R.B., 2010. Interpretation of the CPT in engineering practice. Key note lecture 2. [In:] P.K. Robertson (Ed.): *Proceedings of 2nd International Symposium on Cone Penetration Testing*. Huntington Beach, Omnipress, 19 pp.

Borówka, K.R., 1980. Współczesne procesy transportu i sedymentacji piasków eolicznych oraz ich uwarunkowania i skutki na obszarze wydm nadmorskich. [Present-day transport and sedimentation processes of aeolian sands – controlling factors and resulting phenomena in a coastal-dune area]. *Poznańskie Towarzystwo Przyjaciół Nauk, Prace Komisji Geograficzno-Geologicznej* 20, 126 pp.

Casagrande, A., 1936. The determination of the preconsolidation load and its practice significance. *Proceedings of 1st International Conference on Soil Mechanics and Foundation Engineering* (Cambridge) 3, 60–64.

Dobracka, E. & Pisarska, M., 2002. Plejstocen Pomorza Środkowego i strefa marginalna lobu Parsęty. Stanowisko Ostrowąs [Pleistocene of Middle Pomerania and the marginal zone of the Parsęta ice-sheet lobe. Site Ostrowąs]. *IX Konferencja Stratygrafia Plejstocenu Polski*. Państwowy Instytut Geologiczny, 131–143.

Frankowski, Z., 2003. Interpretacja wyników sondowań dynamicznych i badań presjometrycznych. Sondowania dynamiczne. [Interpretation of dynamic-probing tests and pressure meter tests. Dynamic sounding]. *Nowoczesne Metody Badań Gruntów,* Instytut Techniki Budowlanej, Warszawa, 12–22.

Gradziński, R., Kostecka, A., Radomski, A. & Unrug, R., 1986. *Zarys sedymentologii* [Principles of sedimentology]. Wydawnictwa Geologiczne, Warszawa, 628 pp.

Jamiolkowski, M., Ladd C.C., Germaine, J.T. & Lancellotta, R., 1985. New developments in field and laboratory testing of soils. *Proceedings of 11th International Conference on Soil Mechanics and Foundation Engineering* (San Francisco), 1, 57–154.

Jamiołkowski, M., Lo Presti, D. C. F. & Manassero, M., 2001. Evaluation of relative density and shear strength of sands from CPT and DMT. *Proceedings of C.C. Ladd Symposium*, M.I.T., Cambridge, 56 pp.

Janbu, N., Tokheim, O. & Senneset, K., 1981. Consolidation tests with continuous loading. *Proceedings of 10th International Conference on Soil Mechanics and Foundation Engineering* (Stockholm) 1, pp 645–654.

Krygowski, B., 1964. *Graniformametria mechaniczna – teoria, zastosowanie*. [A method for mechanical analysis of grain forms – theory and application]. PWN, Poznań, 112 pp.

Locat, J., Tanaka, H., Tan, T.S., Dasari, G.R. & Lee, H., 2003. Natural soils: geotechnical behavior and geological knowledge. [In:] T.S. Tan, K.K. Phoon, D.W. Hight & S. Leroueil (Eds): *Characterisation and engineering properties of natural soils*. Swets & Zeitlinger, 3–28.

Lunne, T., Robertson, P.K. & Powell, J., 1997. *Cone penetration testing in geotechnical practice.* E&FN Spon, London, 302 pp.

Maksiak, S. & Mróz, W. J., 1978. Czwartorzęd środkowej części Pojezierza Pomorskiego [Quaternary of the

middle part of the Pomeranian Lake District]. *Z badań czwartorzędu w Polsce* 19, 97–146.
Mayne, P.W., 1995. Profiling yield stress in clays by in-situ tests. *Transportation Research Record* (National Academy Press, Washington) 1479, 43–50.
Mayne, P.W., 2007. Synthesis on cone penetration testing: state-of-practice. *NCHRP Project* Transportation Research Board (National Academies Press, Washington, D.C.) *20-05, Task 37–14*, 137 pp.
Młynarek, Z., 1979. *Sondowania statyczne i dynamiczne w badaniach geotechnicznych* [Cone penetration testing in geotechnical investigations]. Naczelna Organizacja Techniczna, Poznań, 106 pp.
Młynarek, Z., 2004. Współczesne tendencje wyznaczania parametrów geotechnicznych metodami in-situ [Recent tendencies for the evaluation of geotechnical parameters by means of in situ tests]. *Inżynieria Morska i Geotechnika* 1, 22–27
Młynarek, Z., Tschuschke, W. & Wierzbicki, J., 1997. Klasyfikacja gruntów podłoża budowlanego metodą statycznego sondowania [Soil classification according to cone penetration tests]. *11th Krajowa Konferencja Mechaniki Gruntów i Fundamentowania* (Gdańsk), 119–127.
Młynarek, Z. & Wierzbicki, J., 2007. Nowe możliwości i problemy interpretacyjne polowych badań gruntów [New approaches and investigation problems of in situ tests]. *Geologos* 11, 97–118.
Młynarek, Z., Wierzbicki, J. & Long, M., 2008. Factors affecting CPTU and DMT characteristics in organic soils. [In:] Z. Młynarek, Z. Sikora & E. Dembicki (Eds): *Geotechnical and Maritime Engineering* 1, 407–417.
Pisarczyk, S., 2001. *Gruntoznawstwo inżynierskie* [Engineering soil science]. PWN, Warszawa, 346 pp.
Polska Norma PN – 1981/B-03020: Grunty budowlane. Posadowienie bezpośrednie budowli. Obliczenia statyczne i projektowanie. [Polish standard PN – 1981/B-03020: Building soils. Fundation bases. Static calculation and project]. 24 pp.
Polska Norma PN – 2002/B-04452: Geotechnika. Badania polowe. [Polish standard PN – 2002/B-04452: Geotechnics. Field investigation]. 78 pp.
Radaszewski, R., 2003. *Rekonstrukcja charakterystyk paleokinematycznych wiatrów wydmotwórczych na obszarze Międzyrzecza Warciańsko–Noteckiego*. [Reconstruction of palaeokinematic characteristics of dune-forming winds in the area between the Warta and Noteć rivers]. Instytut Geologii UAM, Poznań, 173 pp.
Radaszewski, R. & Wierzbicki, J., 2007. Charakterystyka zagęszczenia piasków eolicznych i bezpośredniego podłoża wydm na obszarze Międzyrzecza Warciańsko-Noteckiego. [Description of the density of aeolian sands and their substratum in the area between the Warta and Noteć river]. *Geologos* 11, 253–267.
Robertson, P.K., 2009. Interpretation of cone penetration tests – a unified approach. *Canadian Geotechnical Journal*, 46, 1337–1355.
Sanglerat, G., 1972. *The penetrometer and soil exploration*. Elsevier, Amsterdam, 464 pp.
Schnaid, F., 2009. *In situ testing in geomechanics*. Taylor & Francis, London, 329 pp.
Senneset, K., Sandven, R. & Janbu, N., 1989. The evaluation of soil parameters from piezocone tests. *Transportation Research Record* 1235, 24–37.
Sikora, Z., 2006. *Sondowanie statyczne. Metody i zastosowanie w geoinżynierii*. [Statical probing. Methods and practice in geoengineering]. Wydawnictwo Naukowo Techniczne, Warszawa, 350 pp.
Tschuschke, W. & Wierzbicki, J., 1998. Zastosowanie techniki statycznego sondowania do oceny parametrów geotechnicznych podłoża. [Application of the CPT and CPTU techniques to the evaluation of the geotechnical parameters of the subsoil]. [In:] J. Liszkowski (Ed): *Współczesne Problemy Geologii Inżynierskiej w Polsce. [Recent engineering geological problems in Poland]*. Wind, Wrocław, 107–112.
Wierzbicki, J., 2009. Analysis of changes in overconsolidation ratio in selected profiles of non-lithified deposits. *Architecture, Civil Engineering and Environment Journal* 2: 77–84.
Wierzbicki, J., 2010. *Ocena prekonsolidacji podłoża metodami in situ w aspekcie jego genezy* [Evaluation of the subsoil overconsolidation by in situ testing and the problem of deposit origin]. Uniwersytet Przyrodniczy, Poznań, Rozprawy Naukowe 410, 182 pp.
Wierzbicki, J., Paluszkiewicz, Re. & Paluszkiewicz, Ry., 2007. Analiza zmienności litofacjalnej osadów zastoiska złocienieckiego w oparciu o wyniki sondowania statycznego [Lithological analysis of the Złocieniec proglacial lake sediments based on cone penetration test results]. [In:] E. Smolska & D. Giriat (Eds): *Rekonstrukcja dynamiki procesów geomorfologicznych – formy rzeźby i osady* [Reconstruction of geomorphic process dynamics – forms and deposits]. Wydawnictwo Łośgraf, Warszawa, 427–438.
Wierzbicki, J. & Stefaniak, K., 2009. Ocena wpływu struktury i tekstury gruntu niespoistego na opór stożka w badaniu CPTU [Analysis of the influence of a non-cohesive soil structure and texture on the CPTU cone resistance]. [In:] E. Dembicki, M.K. Kumor & Z. Lechowicz (Eds): *Problemy geotechniczne i środowiskowe z uwzględnieniem podłoży ekspansywnych* [Geotechnical and environmental problems of expansive grounds]. Uniwersytet Techniczno-Przyrodniczy, Bydgoszcz, 117–128.