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3D mapping of organic layers by means of CPTU and statistical data analysis

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ABSTRACT: The article presents the possibilities of using selected methods of statistical data analysis to determine the spatial extent of soft soils layers. The test site is characterized by the occurrence of a complex geological structure which is a result of alternating deposition of organic sediments and alluvial sand. As data for the analysis, the CPTU results (calculated to parameters: q_t, Q_t, F_r, I_c) were used. In the analysis, various techniques of data grouping and interpolation were used, including 2D nad 3D IDW methods. Advantages and limitations of each statistical techniques are discussed, both with respect to the geological model of the substrate, and in terms of determining the representative values of geotechnical parameters.

1 INTRODUCTION

Designing the foundation of large-area engineering constructions in complex geological conditions makes it necessary to consider the subsoil structure as a three-dimensional task. The fact, that in geotechnical site characterization we have mostly only point, local and discontinuous data is well known. Simultaneously the construction design assumes a continuous model of the subsoil, in which strength and deformation characteristics are well defined in each point of the space.

The potential solution of this problem is to use the interpolation techniques which can help us to fill in sometimes over of 95% of unknown space, according to some mathematical rules. There are many of interpolation methods, from basic triangulation technique, through a purely analytical technique of square interpolation between testing points – ABOS, a technique based on statistical analysis of the effect of individual observations (Inverse Distance Weighting) to Kriging, in which values of a parameters are determined on the basis of the adopted statistical model of variation of the data. Most of them are developed in two-dimentional space. In this case data distribution is analysed in one plane only, horizontal (a map) or vertical (a cross-section).

A disadvantage of such models is the fact that only data lying on a specific plane is interpolated, and data from the close vicinity, but lying on other levels (for example of depth) are omitted. In the case of complex geology of the site it can lead to inadequate site characterization, for example resulting in miscalculations of settlements of different parts of the construction.

Another important problem is the locality of carried out investigations and the use of different techniques for this purpose. For example borings and CPTU's are carried out simultaneously, but very often in different locations, creating a grid of complementary researches.

The geotechnical models, e.g. a stiffness model, can be assessed using CPTU data, subjected to statistical analysis, quite well (Młynarek et al. 2013). In the case of simple and predictable geology it can be sufficient to use relatively rarely spaced testing points (e.g. testing every 50m). In the case of more complex geology, sometimes it could be necessary, to complete the data set, using some observations from additional and not so advanced investigations. In this case, the problem may occur with the use of analog data from e.g. a drilling log for the assessment of geotechnical models, using digital data, eg. from CPTU.

In this paper authors deal with above problems, and try to show an example of procedure of data interpretation for simultaneous use of a boring log and the CPTU data for a mapping the organic layer in the case of structure sensitive to unequal settlements. The proposed methodology, helps to avoid an important mistakes in the geotechnical site characterization, without any additional time and financial costs.

2 TESTING SITE

2.1 *Geographical and geological characterization*

Research has been carried out in an area in Września, 50 km from Poznań. Września is located on the Wrzesinska Plain in central-western Poland (Fig. 1). Wrzesińska Plain is built of glacial clay, and in the north-western part of the area is an out-wash plain built of layered sand and gravel. In the study area Holocene deposits in the form of silts, glaci-fluvial sands and organic soils also occures.

Deposition of organic soils was an uneven process. Organic deposits on the out-wash plain sedimentation were temporarily backfilled by sandy sediments. As a result of the interim backfill organic soil by sandy deposits, they can be assumed as a sligtly consolidated soil. In addition, analyzed organic soils occurs at different depths and they are characterized by high volatility and lack of regularity in the level, which shows lack of a one main sedimentary basin.

Figure 2 shows examples of drilling profiles. Organic deposits in the form of gyttia and peat are presented at different depths under the fine and medium sand or silty soils. Under the layer of organic soil most frequently a glacial clay is observed.

2.2 *Geotechnical testings*

The test site covered area of a large-area warehouse, designed on a large number of individual footings. Due to the Eurocodes Serviceability Limit State requirements the crucial in this case was to minimize differences between settlements of individual footings. This requires as much as possible precise localization of organic soils layers and as many data as possible for the design.

As part of the research tests the cone pentration tests CPTU and drilling research were carried out. CPTU tests were performed in accordance with the International Reference Test Procedure for Cone Penetration Testing TC-16 Committee ISSMGE (1999). Test points were determined in evenly in the grid after 15 points CPTU and 15 points drilling (Fig.3).

In addition, 3 drilling and 3 CPTU were made at the same points, which were adopted as reference points. Results of drilling were used to identify the occurrence of organic soil in the research profile. In turn, the CPTU were used to determine the mechanical parameters of the organic soils (Fig. 4)

Figure 1. Location of testing site on the country map.

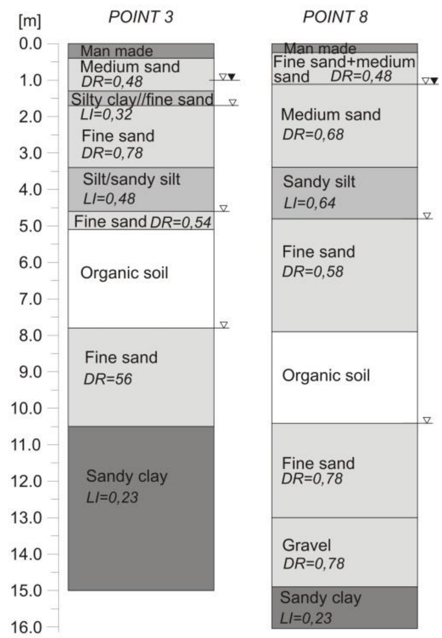

Figure 2. Example of geological profile from the test site (DR – relative density, LI – liquidity index).

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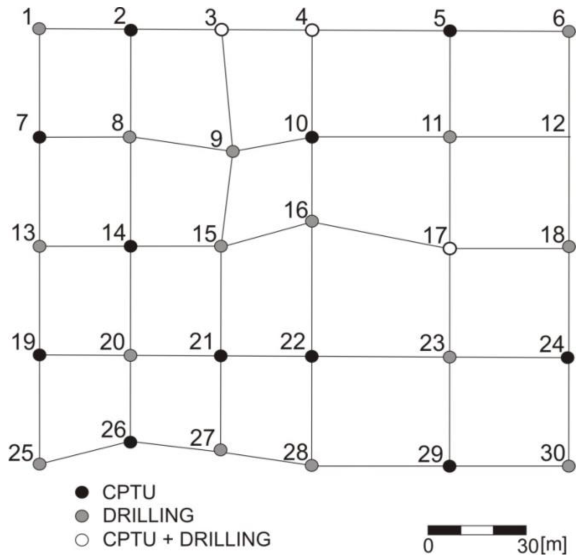

Figure 3. The grid research points.

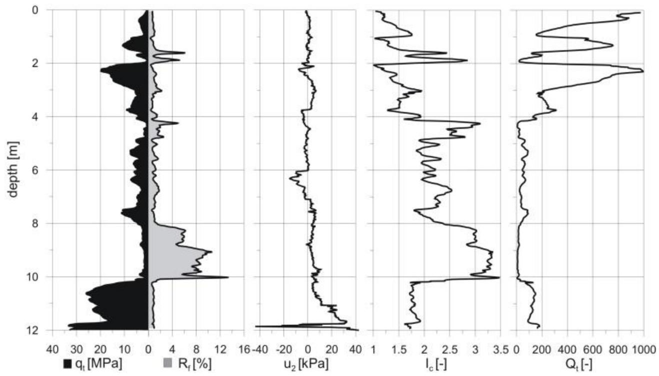

Figure 4. Typical CPTU results (Wrzesnia test site).

A description of organic soils in terms of strength is complicated, and in order to adopt an interpretation procedure for CPTU characteristics, the first step is to verify their position in the Soil Behaviour Type Chart (SBT) (Fig. 5) (Robertson 2009).

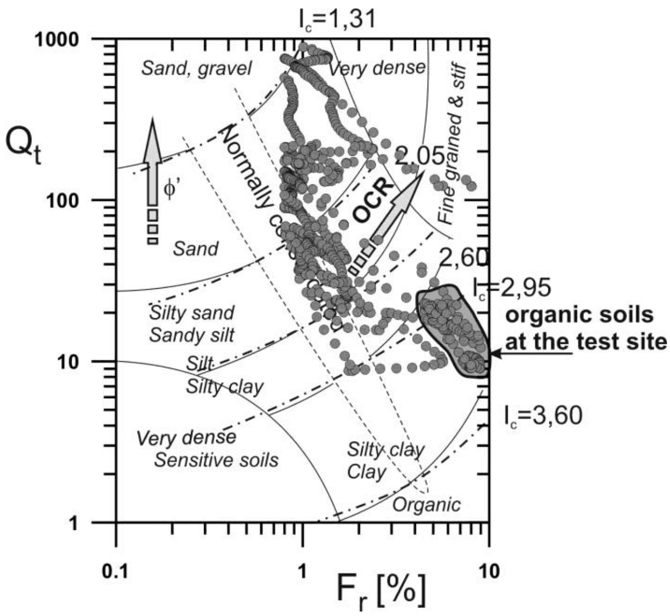

Figure 5. Location of the investigated soils on SBT classification chart.

3 METHODS

3.1 *General assumptions of subsoil model*

As it was stated above, the CPTU and drillings, consisted the almost rectangular grid of 30 testing points, but only half of them provided the complete information about the strength and deformation parameters along the profile. This mean, that in the assessment of e.g. stiffness geostatistical model, the only 50% of gathered information about the configuration of the organic layer, can be used. To omit this disadvantage, the following procedure was proposed. Firstly the CPTU data were calculated to the form of: net cone resistance (q_n), normalized cone resistance (Q_t), normalized friction ratio (F_r), pore pressure parameter (B_q) and soil classification index (I_c). For this purpose the data collected from boring logs were used as well. Secondly, all the CPTU data were mixed all together, and clustered using one of cluster analysis methods. Then the clustered CPTU profiles were compared to the reference profiles, and the average values of CPTU parameters in particular clusters were assigned to individual layers from the boring logs. This let to "digitalize" the lithological profiles and to include the analog information, into the digital set used for the assessment of a geotechnical model. The last step of proposed procedure was to carry out the interpolation of all gathered data. The advantage of this procedure is the possibility of carrying out the geotechnical analysis for the whole investigated space, using so called representative (averaged and statistically grouped) values of the CPTU parameters.

3.2 *Clustering methodology*

Values of the CPTU parameters were subjected to clustering analysis using k-means method which is widely describe and recommended by Młynarek et al. (2005). K-means method is non-hierarchical clustering, consisting in creating defined number of clusters, which differ from each other the greatest extent possible. Every cluster creates a distinct data set. Initial amount of clusters is selected randomly. Objects have been moved between clusters until the minimal intra-cluster variability and maximal inter-cluster variability be achieved (Everitt, 1974). Assigning an object to particular cluster is consisting in comparing the distance of the object from the center of gravity of the cluster.

However, k-means method leads to many possible solutions therefore the problem is the choice of the most appropriate. To dissolve the problem analysis of Calinski-Harabasz index (CH) is conducted. This analysis allows to obtain optimal from a statistical point of view number of clusters (Caliński & Harabasz, 1974). Additionally, optimal number of clusters can be obtained by diagram of weighted average of the coefficient of variation for particular number of clusters (ACV) (Wierzbicki, 2007). The analysis of diagram of weighted average of the coefficient of variation is more engineering tool, because minimalizing the intra-cluster variability simultaneously marginalizing minor clusters. The both methods, analysis of Calinski-Harabasz index and analysis of diagram of weighted average of the coefficient of variation, were used to interpretation of cone penetration tests.

3.3 *2-D and 3-D data interpolation*

The method chosen for interpolation procedure, was the modified Inverse Distance Weighting – IDW. The detailed background of its assumptions was given by Młynarek et al. (2007). In this method the interpolated value of characteristic v_0 in a given point with coordinates (x_0,y_0,z_0) (z_0 is the determined depth) is established on the basis of values of neighbouring v_i, coming from observations in points (x_i,y_i,z_0). Each of these values affects the interpolated value of v_0 with the weight, which is inversely proportional to the distance between these points. The formula used in IDW takes the form:

$$v_0 = \frac{\sum_{i=1}^{|N(v_0)|} w_i v_i}{\sum_{i=1}^{|N(v_0)|} w_i}, \tag{1}$$

where $|N(v_0)|$ denotes the number of included observations from the neighbourhood of v_0, and weight w_i take the form:

$$w_i = \frac{1}{(d_i + s)^p}. \tag{2}$$

The value of d_i found in formula (2) denotes the distance between points (x_0,y_0,z_0) and (x_i,y_i,z_i) in the form:

$$d_i = \sqrt{(x_0 - x_i)^2 + (y_0 - y_i)^2}, \tag{3}$$

in the 2-dimensional case, and:

$$d_i = \sqrt{(x_0 - x_i)^2 + (y_0 - y_i)^2 + \varsigma(z_0 - z_i)^2}, \tag{4}$$

in the case of 3-dimensional interpolation,where $s>0$ and p serve the role of smoothing parameters. By neighborhood $N(v_0)$ we mean here a set of these observations (testing points) at depth z_0, which distance d_i from point (x_0,y_0,z_0) does not exceed a certain fixed threshold value which parameter ζ ($\zeta>0$) was introduced, determining the effect of observations in the direction of axis z, i.e. depth.

4 RESULTS

The cluster analysis carried out on the set of all CPTU data, provided a large number of potential solutions, form 2 to 20 clusters. The choice of the most appropriate one was made using the graphs of the relation of CH and AVC indexes to the number of obtained clusters. As can be seen in the Fig. 6, the CH index shows the statistically best solutions within the frame between 4 and 9 clusters. Simultaneously the value of weighted average of the coefficient of variation (AVC), has the local minimum at 8 clusters. In this case the division of the investigated subsoil into 8 groups was assumed as the most appropriate one.

The next step of analysis was to calculate the representative values of the CPTU parameters for each cluster, and correlate them to the given parts of boring profiles. For this aim the three reference points were used. As the representative values of CPTU parameters the average value was used (Fig. 7). It resulted in the "digitalization" of boring profiles, in which every distinguished layer had been correlated and replaced by representative values of the adequate cluster (Fig. 8).

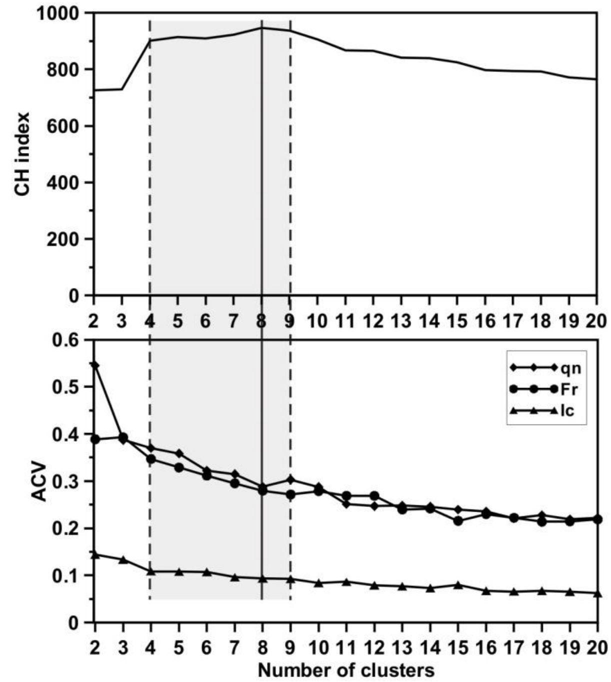

Figure 6. The Caliński-Harabasz CH index and AVC index values, calculated for different numbers of clusters.

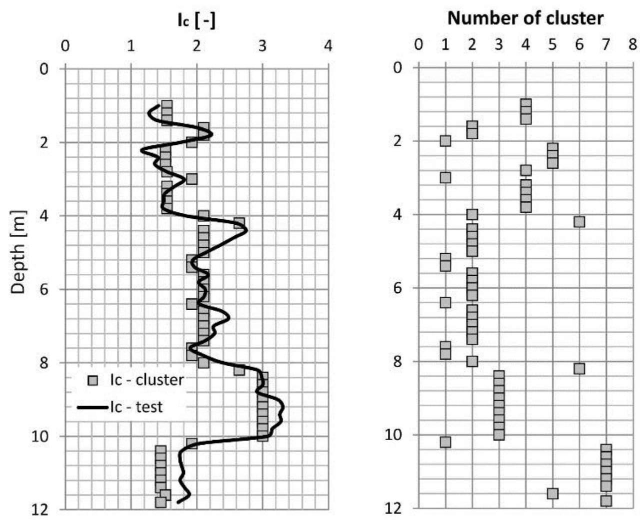

Figure 7. An example of the I_c profile from CPTU (test) and obtained after cluster analysis on the background of the profile division into the clusters.

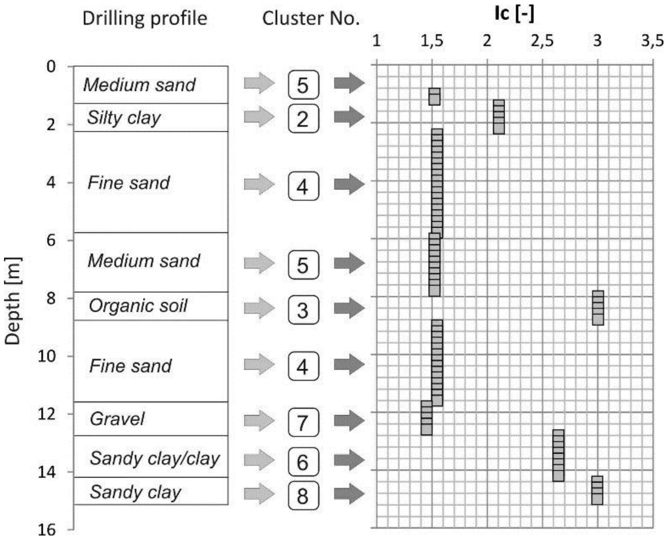

Figure 8. An example of the conversion of drilling profile into I_c profile on the basis of correlated clusters.

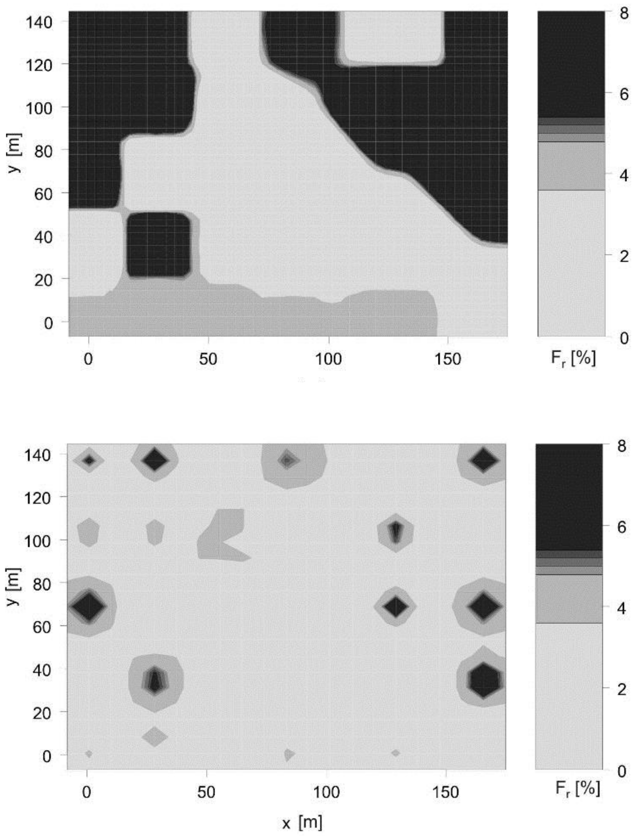

Figure 9. The 2-D interpolation model (above) and 3-D interpolation model (below) of Fr, showed at the depth of 8,4 m.

So prepared set of the data was subjected to the interpolation analysis. For the purpose of this part of analysis two CPTU parameters were chosen: F_r and I_c. This selection of the first of them resulted from the fact that, as it was observed during the cluster analysis, the value of F_r above 5,3 indicates an organic soil very well. At the same time the I_c values not allows to distinguish clearly boundary between organic soils and sandy clays, but can be very helpful for the analysis of the strength properties of subsoil.

Both the 3-D and 2-D analysis were carried out, resulting in the models of distribution of analyzed parameters in the investigated space and providing almost continuous data at the whole investigated area. As an example of obtained results the maps created at the depth of 8,4 m are presented and discussed.

Despite to the results obtained by Młynarek et al. (2007), present investigations show almost complete inadequacy of the 3-D model in comparison to 2-D model (Fig. 9). The organic layer, indicated by F_r values above 5,3 %, is almost not identified in the case of 3-D model, despite to 2-D model. The 2-D model clearly allows to determine the extent of organic soil at a given depth, using F_r parameter. Additionally, a level of risk of adopting the incorrect geotechnical model in the analyzed case, can be observed if we calculate the 2-D model, at the same depth, but using only CPTU data (Fig. 10). It is clearly seen that additional data from drillings provide an important knowledge about the extent of the organic layer. This fact results in the possibility of distinguish the potentially week zones within the subsoil, by means of analysis of I_c parameter (Fig. 11). In the analyzed case a value of I_c above 2,8 indicated not consolidated clays or organic soils, which may result in increased settlements of footings.

5 CONCLUSIONS

Proper site characterization is one of the most important stages of any investments. In the described example the crucial for the footings design of warehouse was to localize the organic layer, and to digitalize the information on the geotechnical properties for the purpose of structural model. For this purpose both CPTU measurements and drilling logs were used, providing data for statistical model of subsoil.

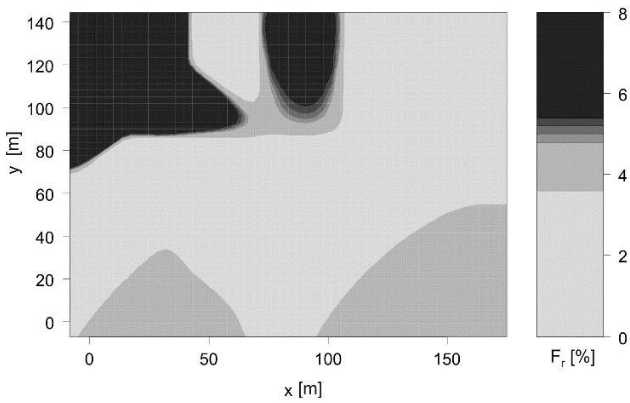

Figure 10. The 2-D interpolation model of F_r at the depth of 8,4 m, calculated for the CPTU data only.

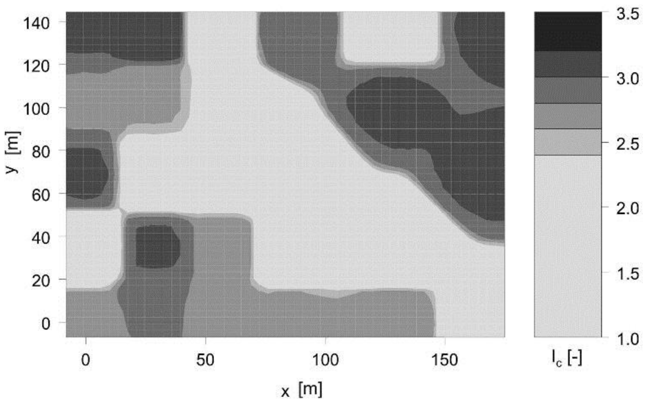

Figure 11. The 2-D interpolation model of I_c at the depth of 8,4 m.

It was clearly seen that only simultaneous use of all available data allowed the detailed identification of organic soil layer. This in turn was possible by subjecting the CPTU data to cluster analysis and then to use all data for computation of interpolation IDW model.

Despite to the arrangement done by Młynarek et al. (2007), the full 3-D IDW model has not yielded a satisfactory results. This is probably due to highly horizontal extent of the mapped organic layer and also a high contrast in values of analyzed parameters between organic soil and the rest of subsoil.

Finally, on the basis of computed IDW model of CPTU parameters it is possible to calculate geotechnical parameters, as constrained modulus or shear strength parameters, in any point of investigated space.

6 REFERENCES

Caliński, T. & Harabasz, J. 1974. A dendrite method for cluster analysis. *Communication in Statistics*, 3: 1-27.

Everitt, B. 1974. Cluster Analysis. Halsted-Wiley. N.Y.

Młynarek, Z., Wierzbicki, J. & Wołyński, W. 2005. Use of cluster method for in situ tests. *Stud. Geotech. Mech*, 27, 3/4: 16-27.

Młynarek, Z., Wierzbicki, J. & Wołyński, W. 2007. An approach to 3D subsoil model based on CPTU results. V. Cuellar et. al (eds.) *Geotechnical Engineering in Urban Enviornment,*. Vol. 3, 1721-1726. Millpress, Rotterdam.

Młynarek, Z., Wierzbicki, J. & Stefaniak, K. 2013. Deformation characteristics of overconsolidated subsoil from CPTU and SDMT tests. R. Q. Coutinho& P.W. Mayne (eds.) *Geotechnical and Geophysical Site Characterization 4,. Proc. of 4th International Conference on Geotechnical and Geophisical Site Investigations:* 1189-1193.Taylor & Francis Group, London.

Robertson, P. K. 2009. Interpretation of Cone Penetration Testing – a unified approach, Canadian Geotechnical Journal, 46 (11), 1337–1355.

TC-16 (1999) ISSMGE International Reference Test Procedure for Cone Penetration Test (CPT) and Cone Penetration Test with Pore Pressure (CPTU).

Wierzbicki, J. 2007. Determination of homogenous geotechnical layers in strongly laminated soil by means of CPTU and cluster analysis. V. Cuellar et. al (ed.) *Geotechnical Engineering in Urban Enviornment,*. Vol. 5, 575-579. Millpress, Rotterdam.