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DEEP COMPACTION CONTROL OF SANDY SOILS

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Abstract: Vibroflotation, vibratory compaction, micro-blasting or heavy tamping are typical improvement methods for the cohesionless deposits of high thickness. The complex mechanism of deep soil compaction is related to void ratio decrease with grain rearrangements, lateral stress increase, prestressing effect of certain number of load cycles, water pressure dissipation, aging and other effects. Calibration chamber based interpretation of CPTU/DMT can be used to take into account vertical and horizontal stress and void ratio effects. Some examples of interpretation of soundings in pre-treated and compacted sands are given. Some acceptance criteria for compaction control are discussed. The improvement factors are analysed including the normalised approach based on the soil behaviour type index.

Key words: *vibrocompaction, CPTU, sands, soil behaviour type*

1. INTRODUCTION

The reclamation works in civil and maritime engineering together with the compaction of existing deposits of cohesionless soils increase the use of deep soil compaction. The complex mechanism of deep soil compaction is related to void ratio decrease with grain rearrangement, lateral stress increase, prestressing effect of certain number of load cycles, water pressure dissipation, aging and other effects. An important issue is the choice of the appropriate method of the compaction control, the test parameters and the compaction criterion to be fixed. CPTU is the most widely used method for deep compaction verification (Schmertmann [1], Mesri et al. [2], Slocombe et al. [3], Massarsch and Fellenius [4]). However, it is not so sensitive to the stress history, lateral stress increase and prestressing effect as DMT and CPTU cannot fully take into account the major phenomena related to the soil improvement due to deep compaction (Marchetti et al. [5], Lee et al. [6]). Additional advantage of DMT or pressuremeter test (Gambin [7]) in quality control is that they provide supplementary data on soil deformability and stress state. It is thus possible to get a comprehensive measure of compaction control including the soil strength and deformability characteristics. The application of CPTU and DMT in quality control of compaction works will be discussed in this paper.

2. COMPACTION CRITERIA

The criteria for the compaction control can be fixed in terms of relative density, specific value of cone resistance, modulus of deformation and soil settlements on the trial field. CPTU is particularly useful when a certain relative density over the compacted strata should be obtained. Taking into account the soil mineralogy and compressibility at a given site, the suitable correlation – established from calibration chamber tests – between the cone resistance and relative density should be applied. The improper estimation of the sand compressibility can produce the uncertainty in the evaluated relative density up to 20%. One should also remember that these correlations are established from calibration chamber tests on freshly deposited sand, their use for in-situ conditions and in aged or cemented sands gives an equivalent relative density (Schmertmann et al. [1], Jamiolkowski et al. [8]).

The choice of a specific value of cone resistance as a compaction criterion over the strata considered will produce an excessive compaction effort in the upper layers and non uniform soil densification. The better solution is to express (Massarsch and Fellenius [4]) compaction specification as a cone resistance value adjusted to mean effective stress.

If the compaction requirement is to obtain a minimum modulus of deformation in the strata considered, then the dilatometer or pressuremeter is a very useful tool to check the compaction effectiveness. The constrained modulus from dilatometer test M_{DMT} can be considered simply as one-dimensional, compression modulus M, because the settlement observations of the real structures (Schmertmann [1], Marchetti et al. [5]) are very consistent with those calculated with the constrained moduli from DMT (i.e., $M \approx M_{DMT}$). Values of the constrained modulus from DMT can be thus compared directly to the fixed criterion. When a minimum value of the relative density should be obtained in the compacted strata, the DMT is useless because no method is available to derive the relative density from dilatometer test data alone (Marchetti et al. [5]).

3. GDYNIA PORT CASE HISTORY

A set of buildings was designed near the President Harbour in Gdynia Port. Heterogeneous soil conditions – with Holocene sand containing some mud inclusions and sand fills of variable thickness – imposed the soil improvement under the slab foundation. The vibro-compaction method was applied for densifying sandy soils by means of electric vibrating unit. Under the influence of vibration in fully saturated conditions loose sand particles are rearranged into a denser state with simultaneous increase of lateral stress in the soil mass.

3.1. SOIL CONDITIONS

A simplified soil cross section is given in Fig. 1. Sand fills and aged Holocene sands with silt and mud inclusions are found. The water table is about 1 m below the ground level. Some parts of the superficial layers were hydraulically placed fills. Below dense sand found near the surface a medium dense to loose sand is found with local seems of silts or mud. Loose sand with silt and mud inclusions was detected near the harbour from 9 to 11 m. A very dense Pleistocene sand is found below. The roof of a very dense Pleistocene sand declines towards the harbour.

3.2. COMPACTION WORKS

Deep soil vibratory compaction with granular material supply from the surface was used. S-type vibrator with power 120 kW, frequency 30 Hz and vibration amplitude of about 20 mm was used. The application of infill material assists in maintaining site levels. It provides an additional increase of the lateral stress within the subsoil, induces arching phenomena – extra reducing the expected settlements. Compaction was performed in regular square grid 3 × 3 m. Neither water nor air was introduced during the vibrator insertion and the consecutive compaction phases. The area to be compacted was about 7000 m^2. The soil thickness subjected to vibro compaction increases towards the harbour.

During the works typical parameters were recorded. The settlements of the soil surface due to deep soil vibratory compaction were monitored. Up to 44 cm

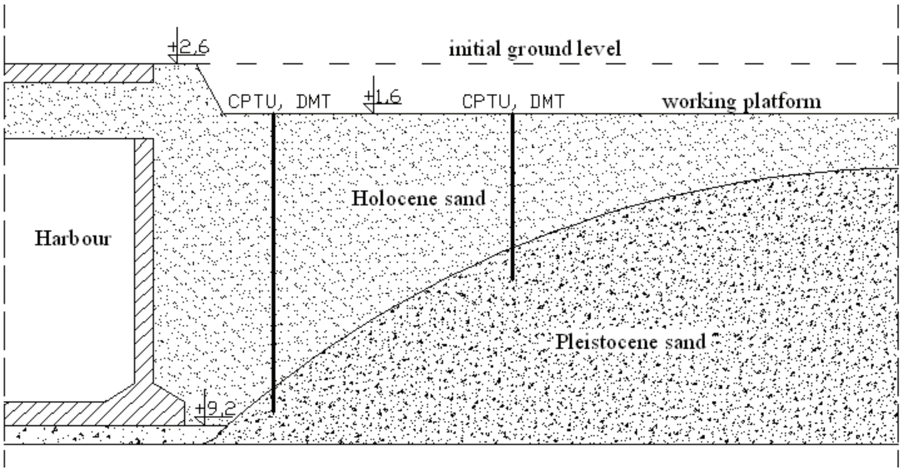

Fig. 1. Simplified cross section (not to scale), Bałachowski and Kozak [9]

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of the surface settlement was measured within the compacted area. The consumption of infill was monitored at each point of vibratory compaction. The power input was controlled and recorded in each profile of vibratory compaction. The minimum average constrained modulus over the soil profile equal 80 MPa was fixed as an acceptance criterion for the post-treated subsoil.

3.3. CPTU/DMT CONTROL TESTS

The control tests were realised, midway between the points of vibration, more than 3 weeks after the works had been completed. These tests were made close to the preliminary tests in order to compare pre-treatment and post-treatment soil characteristics. CPTU and DMT tests were performed and typical characteristics were calculated.

The normalised friction ratio F_r is obtained

$$F_r = \frac{f_s}{q_t - \sigma_{v0}}, \tag{1}$$

where:

f_s – sleeve friction,
Q_T – CORRECTED CONE RESISTANCE,
σ_{v0} – total overburden stress.

Three intermediate parameters (I_D, K_D, E_D) and constrained modulus M_{DMT} from DMT are defined (Marchetti [10]):

- material index

$$I_D = \frac{p_1 - p_0}{p_0 - u_0}, \tag{2}$$

- lateral stress index

$$K_D = \frac{p_0 - u_0}{\sigma'_{v0}}, \tag{3}$$

- dilatometer modulus

$$E_D = 34.7(p_1 - p_0), \tag{4}$$

where

p_0, p_1 – corrected pressures from DMT,
u_0 – hydrostatic pressure,
σ'_{v0} – effective overburden stress.

$$M_{DMT} = R_M E_d \tag{5}$$

where R_m – empirical coefficient dependent on I_D and K_D.

The results before and after compaction are compared for CPTU (Fig. 2) and DMT (Fig. 3) tests. The CPTU and DMT tests before compaction were performed from the initial ground level. The control tests were realised from the working platform. Due to planning, levelling of the surface area and the soil settlements induced by deep compaction the plots are shifted about 1.4 m. The soil layer subjected to compaction has here the thickness of 8 m. An important, up to 5 times, increase of cone resistance and a slight sleeve friction augmentation are observed within the compacted layers. The corresponding normalised friction ratio decreases after deep compaction, which is consistent with general observations (Slocombe et al. [3], Debats and Scharff [11]).

A considerable augmentation of dilatometer and constrained moduli from DMT (Fig. 3) is obtained, more pronounced than the changes in cone resistance. An important growth of the lateral stress index K_D in post-treated soil was recorded due to soil density increase, soil prestraining and lateral stress increase, as it senses different components of stress history changes during compaction process (Marchetti et al. [5]). The constrained DMT modulus over the compacted soil strata exceeds by far the acceptance crite-

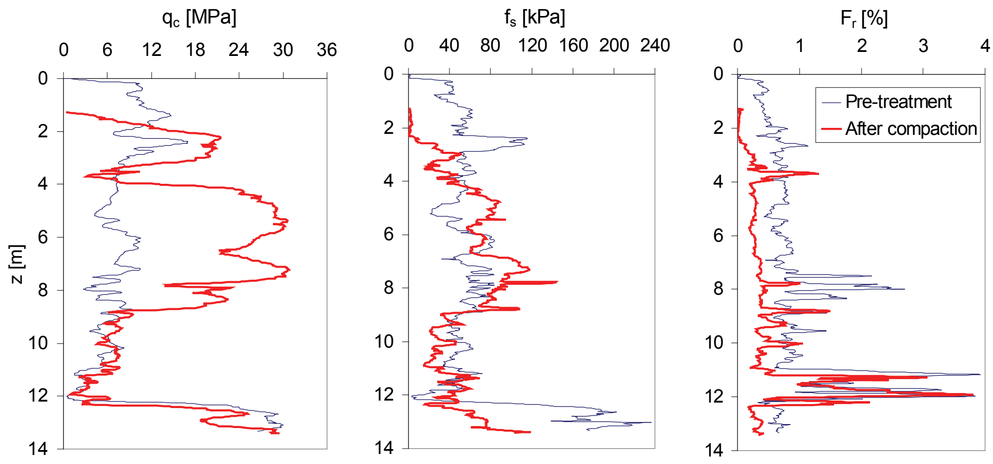

Fig. 2. Comparison of pre- and post-treatment CPTU results, Bałachowski and Kozak [9]

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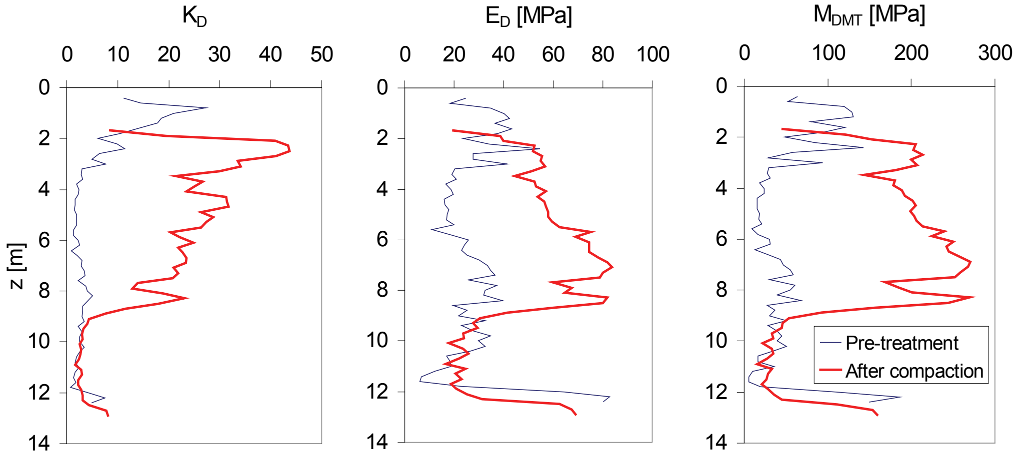

Fig. 3. Comparison of pre- and post-treatment DMT results, Bałachowski and Kozak [9]

rion. The post-treatment constrained modulus is even up to 10 times higher than before compaction (Fig. 3).

4. SOIL TYPE BEHAVIOUR

4.1. CLASSIFICATION CHARTS

Different CPTU soil behavioural type charts were elaborated recently (Schneider et al. [12], Robertson [13], Cetin and Ozan [14]), specially to describe silty sands or intermediate soils. These charts are based on the soil type behavior and not on the soil granulometry. As fine to medium sands are considered to be predominant in this case study the typical Robertson and Campanella chart (1986) was used to present the soil behaviour and the soil classification before and after compaction works (Fig. 4). After treatment the majority of the points on the diagram were translated from area 8 to 9 and 10. While the soil granulometry remains the same after vibrocompaction its behavior changes from typical for silty sands to be classified as corresponding for clean sands or even gravelly sands. This shift of the points can be partially attributed to relative density increase as given in Fig. 4. Due to compaction the normalised friction ratio decreases as was already observed in Fig. 2.

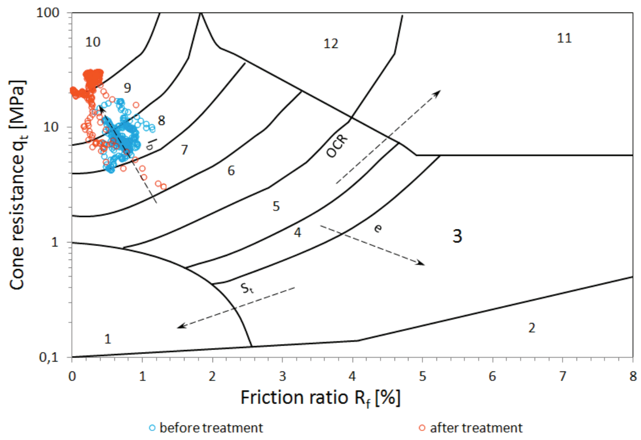

Fig. 4. Soil classification chart according to Robertson and Campanella (1986), Lunne et al. [15]

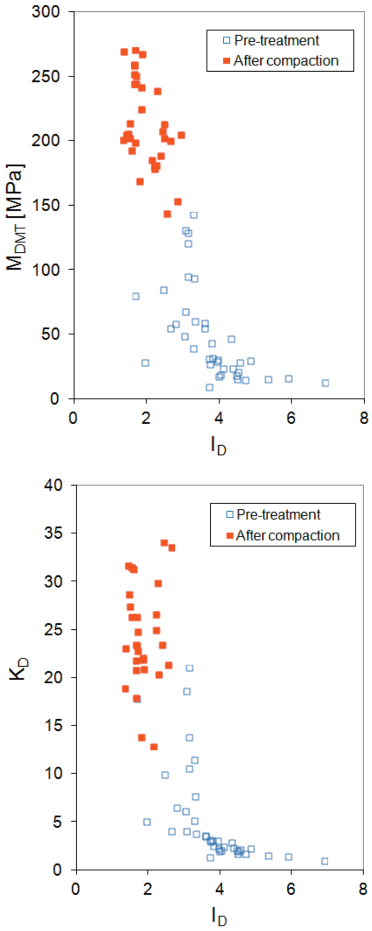

Fig. 5. Constrained modulus from DMT and lateral stress index vs. material index

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A certain analogy exists between the normalised friction ratio F_r and lateral stress index I_D in DMT (Marchetti et al. [5]) as both are used to delineate soil behaviour type. The constrained modulus M_{DMT} and lateral stress index K_D for pre-treated and compacted subsoil were compared (Fig. 5). While considerably higher modulus of deformation and lateral stress index are registered after compaction, the soil exhibits slightly lower values of the material index I_D. These are however higher than the lower boundary limit 1.8 for soils behaving like sands. This finding needs to be verified in other test conditions.

4.2. SOIL TYPE BEHAVIOR INDEX I_c

A simple comparison of pre- and post-CPT profiles can provide a ground improvement factor as the ratio of average cone resistance after treatment to average cone resistance before treatment. The presence of layers with higher fines content, local seems of soft material and some needs for cone resistance normalisation with depth make so defined improvement factor difficult to calculate and analyse.

A new approach in estimation of soil improvement factor was proposed (Debats and Scharff [11]) to take into consideration the soil heterogeneity and cone resistance stress normalisation. The normalised cone resistance Q_t is calculated

$$Q_t = \frac{q_t - \sigma_{v0}}{\sigma'_{v0}}. \tag{6}$$

The soil behaviour type index is defined (Lunne et al. [15]) as

$$I_c = [(3.47 - \log Q_t)^2 + (\log F_r + 1.22)^2]^{0.5}. \tag{7}$$

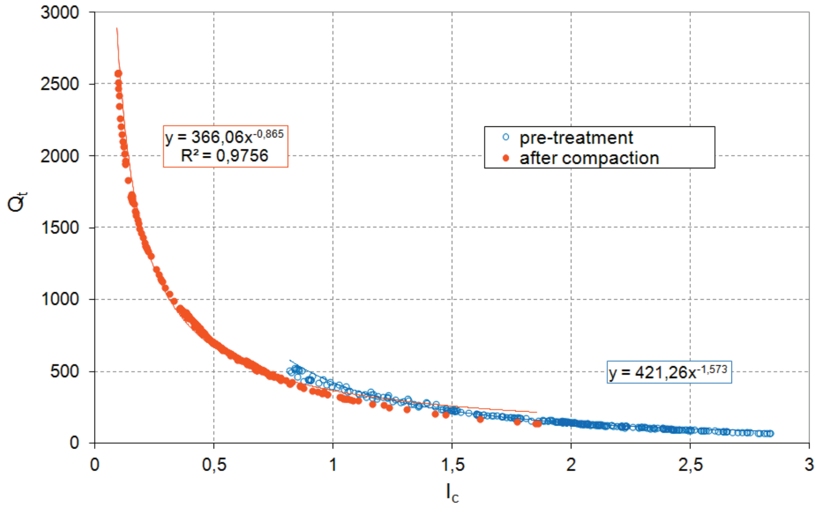

Fig. 6. Normalised cone resistance vs. soil behaviour type index

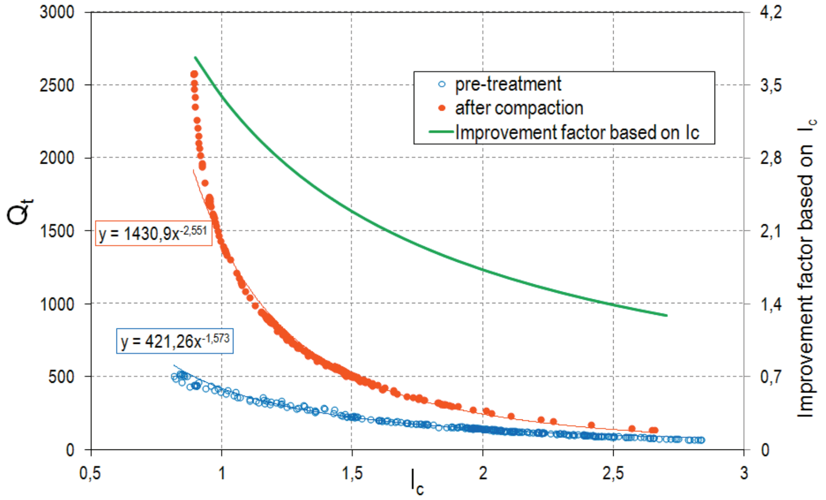

Fig. 7. Shifted normalised cone resistance and improvement factor based on soil behaviour type index

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The normalised cone resistance calculated in the soil profile before and after compaction as a function of soil behaviour type index is given in Fig. 6. The data after compaction are translated towards lower I_c values. It means that the soil behaviour type changes from silty and sandy mixtures to sands and sands and gravels.

The improvement factor based on soil behaviour type index is calculated as follows:

- The curve normalised cone resistance versus soil behaviour index for the soil after compaction is shifted to the right to meet the range of I_c values for the pre-treated soil.
- The improvement factor based on I_c is calculated as a ratio of normalised cone resistance after and before compaction for given values of soil behaviour type index.
- This improvement factor is plotted in Fig. 7.

The highest improvement factor based on I_c is obtained for the soil behaviour type corresponding to sands and sands and gravel. The effect of the improvement is getting smaller for higher values of soil behaviour type index before compaction. As stated by Debats and Scharff [11] slightly higher values of the improvement factor based on I_c are found compared to these obtained directly from cone resistance. Further analyses are necessary to check validity of this approach in sands of different mineralogy and higher fines content.

5. CONCLUSIONS

Quality control of deep soil vibratory compaction was realised with coupled CPTU and DMT tests. An important increase of cone resistance, lateral stress index, dilatometer and constrained DMT moduli was measured within the compacted sandy soil. The cone resistance in the post-treated sand increased 2.5 times on average. The constrained modulus from DMT in compacted sand was 7 times higher than in the pre-treated sand. The improvement criterion – fixed as a certain value of the constrained modulus – was achieved by far within the compacted layer. Marginally compactable or uncompacted layers were easily found with CPTU and DMT. Analysis of soil type behaviour using the classification charts and soil type behaviour index I_c provides better, more comprehensive and normalised approach to the soil improvement. The procedure proposed by Debats and Scharff [11] was successfully tested. Here, one can determine overall improvement factor based on I_c regardless of the soil nature and depth. Values of the improvement factor decrease with soil behaviour type index, i.e., with fines content. The first attemps to introduce soil behaviour type approach to DMT tests were also applied in compaction control.

REFERENCES

[1] SCHMERTMANN J.H., *Dilatometer to compute foundation settlements*, Proc. In-situ'86 GT Div., ASCE, June 23–25, Blacksburg, VA, 1986, 303–321.

[2] MESRI G., FENG T.W., BENAK J.M., *Postdensification penetration resistance of clean sands*, J. Geotech. Engng., ASCE, 1990, 116, 7, 1095–1115.

[3] SLOCOMBE B.C., BELL A.L., BAEZ J.I., *The densification of granular soils using vibro methods*, Géotechnique, 2000, 50, 6, 715–725.

[4] MASSARSCH K.R., FELLENIUS B.H., *Vibratory compaction of coarse-grained soils*, Can. Geotech. J., 2002, 39, 695–709.

[5] MARCHETTI S., MONACO P., TOTANI G., CALABRESE M., *The flat dilatometer test (DMT) in soil investigations*, A report by the ISSMGE Committee TC16. Proc. In-situ 2001, Bali, May 21, 2001, 41 pages.

[6] LEE M.-J., CHOI S.-K., KIM M.-T., LEE W., *Effect of stress history on CPT and DMT results in sand*, Engineering Geology, 2011, 117, 259–265.

[7] GAMBIN M., *Le pressiomètre Ménard, un excellent outils de côntrole d'amélioration des sols*, 1995, Proc. Première Journée Louis Ménard, CMFS, Paris 1995.

[8] JAMIOLKOWSKI M., LO PRESTI D.C.F., MANASSERO M., *Evaluation of relative density and shear strength of sand from CPT and DMT*, C.C. LADD Symposium, M.I.T., Cambridge, Mass., October, 2001, 37.

[9] BAŁACHOWSKI L., KOZAK P., *Compaction control at Gdynia Port with CPTU and DMT*, Proc. of International Symposium of vibratory pile driving and deep soil vibratory compaction, Transvib, September, LCPC Paris 2006, 121–129.

[10] MARCHETTI S., *In situ tests by flat dilatometer*, Journal of the Geotechnical Engineering Division, ASCE, 1980, 106, 3, 299–321.

[11] DEBATS J.M., SCHARFF G., *Robertson's Soil Behaviour Type Index as a tool to measure the improvement of the ground in vibrocompaction works*, André Frossard Prize, 2009.

[12] SCHNEIDER J.A., RANDOLPH M.F., MAYNE P.W., RAMSEY N.R., *Analysis of factors influencing soil classification using normalized piezocone tip resistance and pore pressure parameters*, Journal of geotechnical and geoenvironmental engineering, 2008, 134, 11, 1569–1586.

[13] ROBERTSON P.K., *Interpretation of cone penetration tests – unified approach*, Canadian Geotechnical Journal, 2009, 46, 1337–1355.

[14] CETIN K.O., OZAN C., *CPT-based probabilistic soil characterization and classification*, Journal of Geotechnical and Geoenvironmental Engineering, 2009, 135, 1, 84–107.

[15] LUNNE T., ROBERTSON P.K., POWELL J.J.M., *Cone Penetration Testing in Geotechnical Practice*, Blackie Academic and Professional, 1997.

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