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CPTU IN SOFT POST-FLOTATION SEDIMENTS

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1. INTRODUCTION

The history of copper ore mining in the Lower Silesia, a region in south-west Poland, goes back to the XIX century when the first shafts were bricked off. Since that time the industry has been continuously developed up to this day. One of the most important event in its history, i.e. establishing of KGHM Polska Miedź S.A., the managing company being now ranked as the seventh largest copper supplier and the second of silver supplier in the world took place in 1961.

Unfourtunately, only 5% of mineral product includes copper ore; the remaining part is from the technological point of view completely useless. Mineral wastes – this is a proper name – are very specific kind of soil. Although at first sight they strongly resemble natural soil, they are in fact a man-made material being a by-product of technological process in which the metal-bearing rock is crushed to small fractions, varying from fine sand to clay particles. This posed a serious problem of mineral waste deposition, the solution of which turned out to be post-flotation sediment dumps. Of six dumps in the region, the newest is the reservoir of Żelazny Most, located between Lubin and Głogów. Started in 1977, today of the height exceeding locally even 45 m, the diameter of approximately 5 km, the length of dams over 14 km and accumulation capacity of 350 million m^3 it is the biggest hydrotechnical construction in the world. Taking advantage of water, the crushed rock is sent to the reservoir through a wide net of pipelines. This transport method allowing dumping of the waste material is responsible for a significant variability of not only its grain-size distribution, but also of its physical parameters which affects the drainage conditions.

Because of the complexity of the Żelazny Most project, several scientific centers and institutes both from all over the Poland and Europe (e.g. Norwegian Geotechnical Instuitute) have been involved in its supervision; moreover, International Experts' Board – an advisory body – was also established. Due to their efforts, the CPTU test was decided to be a reliable method of assessing current effective stress conditions. However, it soon became clear that interpretation of the data on artificial soils such as mine tailings had to be improved to some extent. Because of their special character, local correlations between penetration characteristics and shear strength parameters or deformations characteristics of post-flotation deposits should be found.

2. INVESTIGATIONS

Due to the deposition and heigthening method, in the cross-section of the reservoir three parts can be distinguished (figure 1). First, the dams, surrounding the reservoir, built of the thickest fractions of accumulated material. Second, the so-called beaches, consistig of both non- and cohesive material. Finally – the pond, covering a significant area of the reservoir, in which sedimentation of the finest soil takes place. For many years, geotechnical investigations had been carried out only within the beach and embankments, while the pond did not arouse any interest. There were two reasons for that: difficult access to the area and no need for such actions. However, continuous heightening of dams finally led to the situation, where embankments were built on what had previously been weak part of the dump and therefore, in order to secure the stability of both dump and the reservoir center, the understanding of the “situation” within and below the pond became crucial.

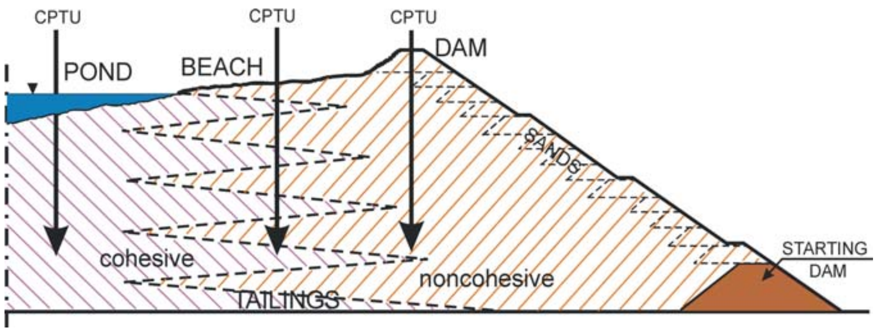

Fig. 1. Parts of the cross-section

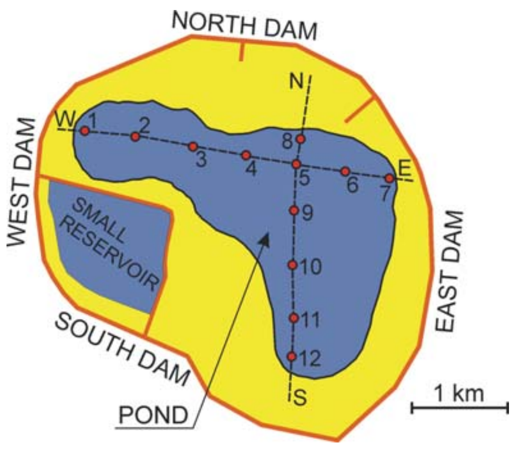

Fig. 2. Carrier’s cross

The first large-scale investigations were conducted in 1993. The site consisted of 12 points constituing two geotechnical cross-sections (later called the Carrier's cross) extending from west to east and from north to south (figure 2). In each of them, the tests of CPTU, DMT and FVT were carried out as well as core samples were taken. The measurements were carried out from a pontoon anchored over each point from four sides and the device used was Hyson 20 TF maufactered by A.P. van dan Berg, world-wide known Dutch company specialized in CPT eqiupment.

During penetration each time three characteristics were measured: the cone resistance q_c, sleeve friction f_s and the pore pressure u_c (standard piezocone was used with a filter placed just behind the cone – u_2) and in the characteristic points of the profile – the pore pressure dissipation. In order to establish in situ values of undrained shear strentgh, several field vane tests were conducted with Polish vane probe PSO-1 (vane size of 80×160 mm, rotation of 5°/min). DMT tests were carried out with a standard Marchetti tip and consisted in measuring the pressure every 20 cm. Samples of the tailings for further laboratory tests were taken with Mostap-65 sampler and were collected into a nylon stocking and a special cointainer in order to avoid the miosture loss and deformations. The laboratory programme was aimed at determination of grain-size distribution, moisture content, volumetric and specific density, Atterberg's limits and also oedometric tests.

3. RESULTS

Unsupraisingly, the results obtained confirmed our previous assumptions. Tailings within the pond (figure 3), consisting mainly of silt fraction, belong to cohesive sediments. The characteristics registered testify to a clear trend of strength increase with depth which reflects the laboratory results. Moreover, the sediments are very weak – the values of cone resistance q_c do not exceed 0.5 MPa, often varying between 0.05 and 0.20 MPa; the values of sleeve friction f_s are also very low and do not go beyond 100 kPa. However, the pore pressure values reach even 500 kPa, close to what is usually observed in natural cohesive soil. Therefore, the assumption can be made that the tailings are not fully consolidated due to self-weight.

The CPTU tests carried out in the beach area (figure 4) delivered completely different data. Both cone resistance and sleeve friction values are high which is in agreement with low values of u_c and short time of dissipation showing that the subsoil is built of non-cohesive, fully consolidated (due to self-weight) material.

Taking into consideration the above facts and at the same time the diagram presented by Robertson (figure 5) it is clear that in case of soft soil of low OCR, the determination of pore pressure u_c is crucial. Therefore, the piezocone CPTU tests have to be conducted. The best correlation between q_c and u_c is achieved based on the undrained shear strentgh S_u, whose values were in this case established in situ.

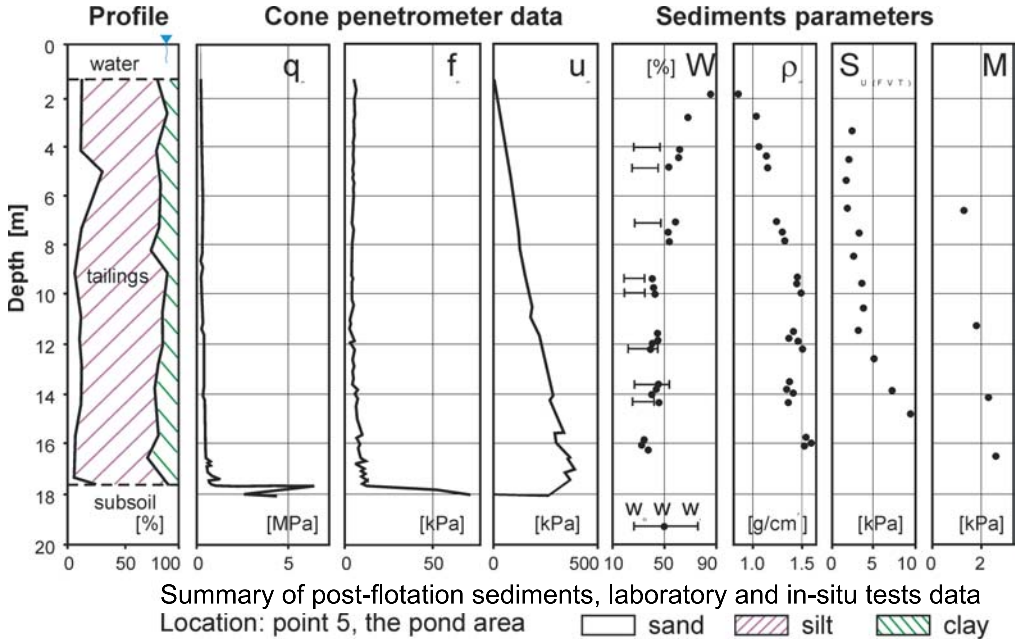

Fig. 3. Typical pond area characteristics

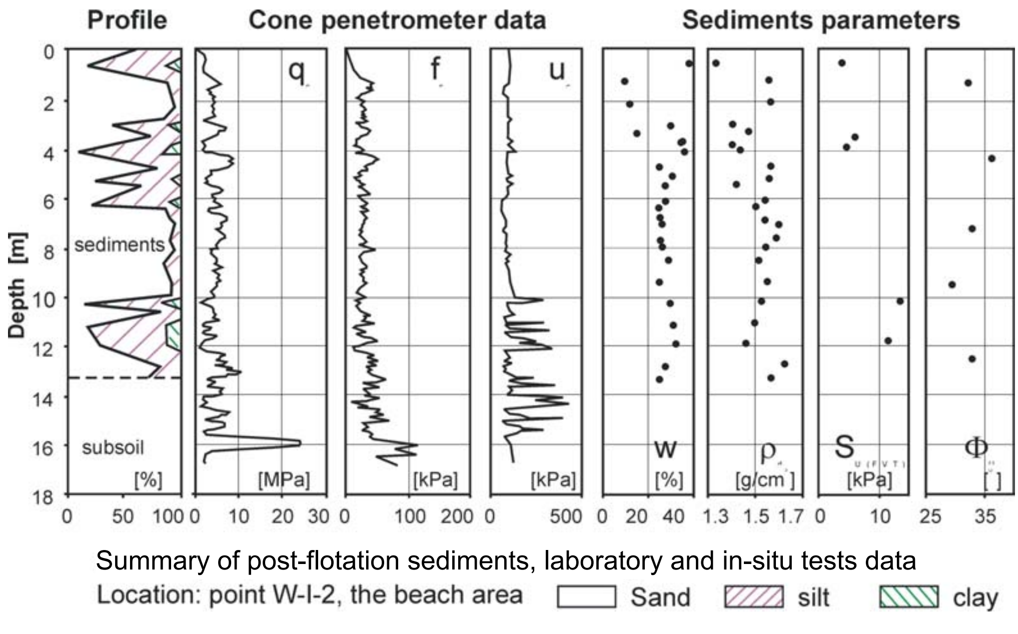

Fig. 4. Characteristics of a typical beach area

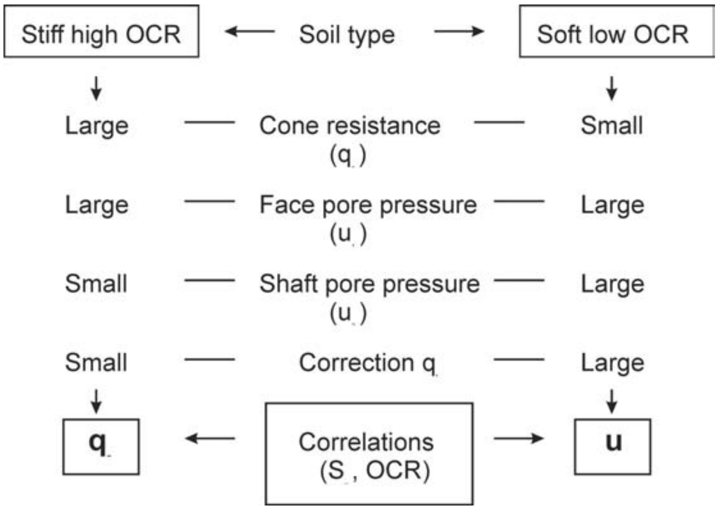

Fig. 5. Robertson's diagram

4. UNDRAINED SHEAR STRENGTH

Obviously, the undrained shear strength can be established in situ, e.g. with FVT test. Nevertheless, geotechnicians have long been trying to avoid this and instead to connect the values of S_u and u_c, the latter being obtained during piezocone penetration CPTU test. As a result two approaches can be distinguished: theoretical and empirical.

Because of some uncertainties about the value of the former one, scientists focused on the empirical solution:

$$S_U = \frac{q_c - \sigma_{v0}}{N_k}, \tag{1}$$

where:

σ_{v0} – total vertical stress,

N_k – empirical cone factor.

The value of N_k depends on many parameters; the OCR of soil and the type of test used for its determination are considered to be most important. The world literature provides the whole range of N_k values; it is enough to mention that for soft Scandinavian clays (Lunne) N_k ranges from 11 to 19 (S_u from FVT), and for overconsolidated North Sea clays (Lunne) N_k = 17 (S_u from triaxial test). In case of post-flotation sediments from Żelazny Most, $N_k = 6.3 \pm 10.1$ ($x \pm S{\cdot}t_\alpha$) at the variability coefficient CV = 0.80 (figure 6).

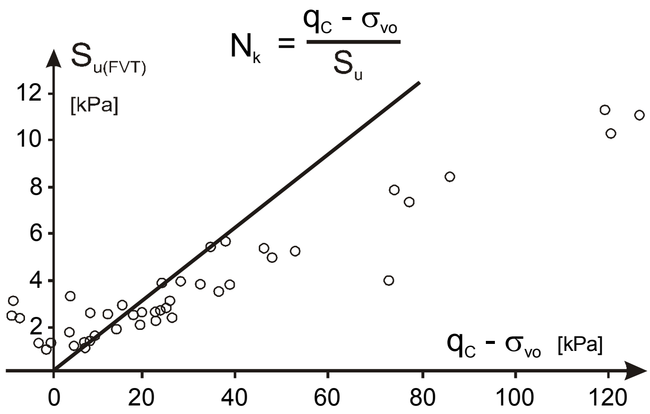

Fig. 6. N_k for post-flotation sediments

The accuracy of N_k may be affected by several factors, the most important of them are lack of the correction for the effect of pore pressure and assumption of complete consolidation conditions. The first issue can be solved by implementation of the corrected cone resistance q_t:

$$q_t = q_c + u_c\,(1 - a)\,, \tag{2}$$

and therefore the value of corrected empirical cone factor $N_{k\,t}$ may be calculated:

$$N_{kt} = \frac{q_t - \sigma_{v0}}{S_U}\,. \tag{3}$$

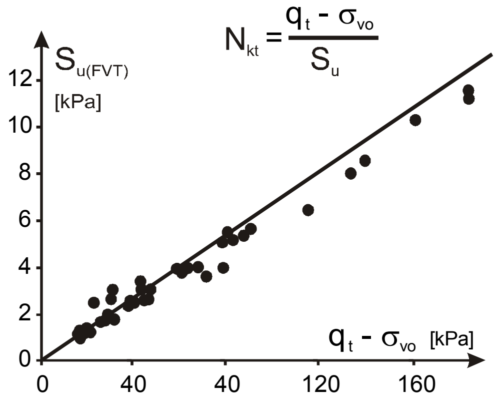

Fig. 7. $N_{k\,t}$ for post-flotation sediments

According to different authors, for minig deposits $N_{kt} = 10.4$ (EAST & ULRICH [1]), for the North Sea clays (Lunne) – depending on OCR – N_{kt} ranges from 8 to 29 (S_u from triaxial test). For the Żelazny Most tailings the value of N_{kt} is 15.6 ± 4.5 ($x \pm S \cdot t_{\alpha}$) at the variability coefficient CV equal to 0.14. This is confirmed by the diagram given in figure 7 from which it can clearly be seen that taking into account the effect of pore pressure and using q_t we can significantly reduce the results' scatter.

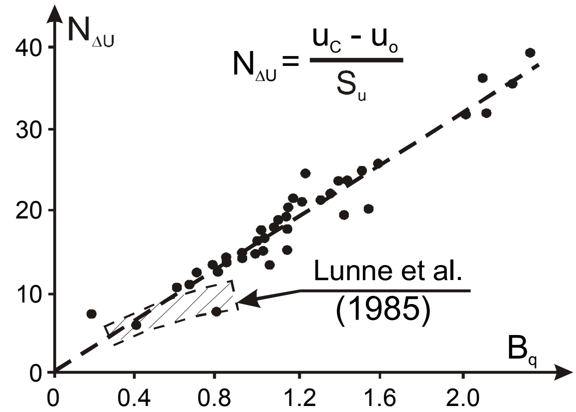

Fig. 8. $N_{\Delta U}$ for post-flotation sediments

Another approach to this problem is to use theoretical or semi-empirical solutions based on the theory of cavity expansion. Therefore, a cone factor for excess pore pressure can be evaluated from:

$$N_{\Delta U} = \frac{\Delta u}{S_U}, \tag{4}$$

where:

$$\Delta u = u_C - u_o. \tag{5}$$

In the case of Canadian clays, $N_{\Delta U}$ obtained from FVT test varies between 7 and 9, wheras its value determined in a consolidated undrained triaxial test ranges from 4 to 10. In this method, q_t is not used directly. $N_{\Delta U}$ can be referred to pore pressure parameter B_q which employs q_t. Figure 8 shows $N_{\Delta U}$ as a function of B_q for post-flotation sediments and compares it with the results presented by Lunne et al.

The last solution, proposed by SENNESET et al. [9], suggests that S_u can be evaluated with use of effective cone resistance q_e and thus the effective cone factor N_{ke} is as follows:

$$N_{ke} = \frac{q_t - u_c}{S_U} = \frac{q_e}{S_U}. \tag{6}$$

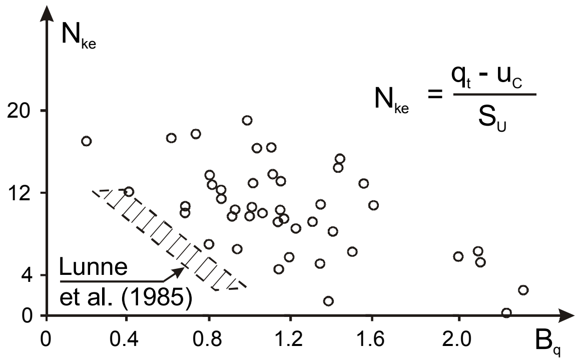

Fig. 9. N_{ke} for post-flotation sediments

There are several N_{ke} values reported in an available literature, among them N_{ke} = 9 ± 3 (Senneset), N_{ke} = 1–13 (Lunne) – both for natural soils, whereas for tailings its value was estimated to be N_{ke} = 1–20. However, the correlation coefficient for N_{ke} in function of B_q for post-flotation tailings at Żelazny Most is so low that this approach must be found as useless in this particular case (figure 9).

5. DISTRIBUTION OF PORE PRESSURE IN SEDIMENTS

In general, soils can be divided into three groups, depending on the type of their consolidation: overconsolidated, normally consolidated and underconsolidated soils. This division, often troublesome for natural soils, is still more complex in the case of post-flotation sediments. It is closely connected with the value of equilibrium pore pressure in situ (u_0) (equations (5) and (7)). This is because the process of consolidation that still takes place in tailings may be responsible for pore pressure that is higher than hydrostatic pore pressure. Similar case was encountered by TANAKA and SAKAGAMI [10] who investigated hydrostatic pore pressure distribution in normally and underconsolidated clays in the Osaka Bay. They concluded that for the former ones, the following equation is valid:

$$\Delta u = \frac{3}{4}(q_t - \sigma_{vo}) , \tag{7}$$

and thus the consolidation may be assessed from a point localization; if it is above the line – the soil under consideration is underconsolidated, and if below the line – the soil is overconsolidated (figure 10). This is another confirmation of the results of investigations conducted at the Żelazny Most – for pond deposits almost all the points are above the line showing clearly that the sediments are underconsolidated.

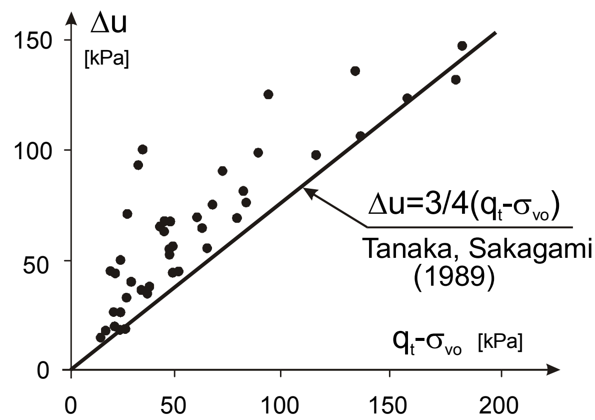

Fig. 10. Excess of pore pressure – corrected cone resistance relationship for pond area sediments

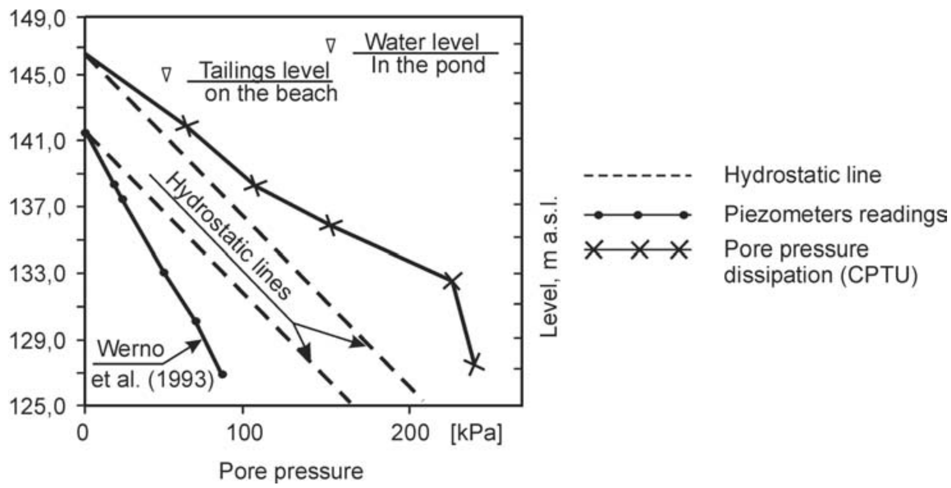

Fig. 11. Pore pressure distribution

Further observations carried out at the object (Werno et al., 1993) also prove that there are significant differences in the values of pore pressure, depending on the localization. In beach sediments, the values of u_0 were lower than hydrostatic values indicating that tailings near embankments were slightly overconsolidated (figure 11). For this reason in situ pore pressure measurements are so crucial.

In general, estimation of the value of u_0 can be achieved with two metods. The first of them is dissipation test until a steady value is reached, and the second one consists in piezometric observations. Both provide data allowing the cone factor calculations resulting in less value scatter and in the values that are on average by 20% lower compared to calculations being based on theoretical values of u_0.

5. DEFORMATION MODULI

Cone penetration test enables also determination of the following soil deformation characteristics: Young's modulus E, shear modulus G, constrained modulus M and initial shear modulus $G_{\max}$. As the problems of undrained shear strength discussed above, the correlations combining moduli and cone resistance are either theoretical or semi-empirical.

In Senneset's method, the constrained modulus M can calculated from the equation:

$$M = m(q_t - \sigma_{v0}) = m\, q_n\,, \tag{8}$$

involving the net cone resistanc q_n and the oedometer modulus number m, the range of which varies from 7 to 13 for the preconsolidation stress and from 4 to 8 for normally consolidated soils.

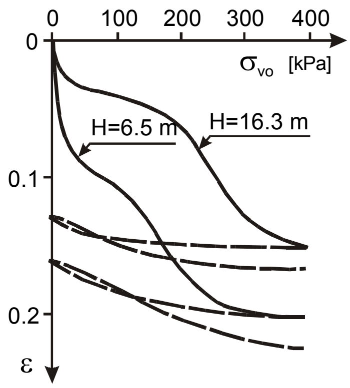

Fig. 12. Oedometer tests for tailings

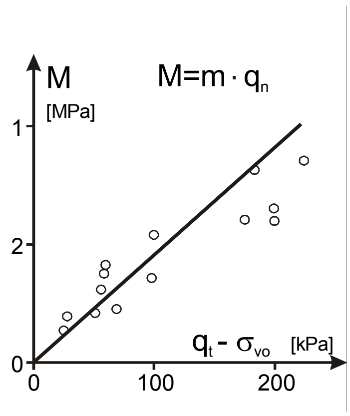

Fig. 13. Secant-oedometer modulus – net cone resistance relationship for tailings

During the investigations at Żelazny Most, tailing samples were taken for laboratory tests. For the samples taken at the depth varying from 5.6 to 17.2 m, the secant-oedometer modulus was determined for the stress range from 0 to preconsolidation stress p'_c; the value M achieved ranged from 0.6 to 35 MPa (figures 12 & 13). At the same time, a mean value of the coefficient m was calculated as m = 18.4 ± 12.3 ($x \pm S{\cdot}t_\alpha$) and exceeded that of natural soils.

6. CONCLUSIONS

Cone penetration test with pore pressure measurement is a method widely used in practice for evaluation of geotechnical parameters of soil, not only natural but also such specific and difficult to describe as mine tailings. It proved to be an excellent device for determining shear strength parameters and characteristics of deformation; it also enables precise registration of stratigraphic changes within a profile and therefore identification of the least favourable layers.

Low bearing capacity of tailings in the pond together with incomplete consolidation process forced the necessary correction of pore pressure. This allowed us to obtain higer values of cone resistance in comparison to uncorrected ones and was possible due to use of CPTU test.

Application of q_t instead of q_c enabled calculation of corrected cone factor N_{kt} which made it possible to determine the undrained shear strength value S_u corresponding to field vane strength. Out of four types of cone factors (N_k, N_{kt}, $N_{\Delta U}$ and N_{ke}) discussed in the paper, this reveals the least scatter of results and therefore is a highly recommendable for post-flotation sediments.

Use of $N_{\Delta U}$ and N_{ke} is limited because their exact in situ pore pressure values have to be known. Analysis of this issue showed that pond tailings behave like underconsolidated soils and therefore in situ pore pressure values are higher than hydrostatic ones. On the other hand, beach tailings strongly resemble slightly overconsolidated soils with u_c values lower than hydrostatic ones. The pore-pressure distribution may be assessed by means of dissipation test.

Finally, CPTU method allows also determination of deformation characteristics of sediments by employing the net cone resistance q_n according to Senneset's formula.

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