WARSAW UNIVERSITY OF TECHNOLOGY Index 351733
FACULTY OF CIVIL ENGINEERING
COMMITTEE FOR CIVIL AND WATER ENGINEERING
POLISH ACADEMY OF SCIENCES ISSN 1230-2945

DOI: 10.24425/ace.2024.149855

ARCHIVES OF CIVIL ENGINEERING

Vol. LXX ISSUE 2 2024

 pp. 135 – 148

Research paper

Mechanical properties of soils in internal waste bank of lignite mines and their primary characteristics

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Abstract: The modern development of urban areas is related to, among others, the location of industrial facilities on the outskirts of cities. More and more often, commercial buildings are founded on areas that have not been used for construction so far. Such areas include, among others: reclaimed lignite mine banks in the Konin region. The man-made soil is a chaotic mixture of fragments of glacial tills and Pliocene clays, often exceeding 20 m in thickness, which is naturally consolidated over time. Due to the method of formation of the embankment, despite the fact that banks are made of natural soil, their strength and deformation characteristics clearly differ from those characteristic of lithologically similar soils deposited as a result of geological processes. In this case, the use of a standard test approach may overestimate the strength and stiffness of the soil. Due to the complex structure of the bank in-situ tests were used for geotechnical exploration: CPTU and FVT, as well as laboratory tests in a triaxial apparatus and an oedometer. The results were compared with the results of studies conducted in similar naturally deposited soils. The obtained results provide valuable geotechnical characteristics of the embankment soil, which in its large fragments is built of natural soil clasts. The obtained results indicate a relatively small change in the geotechnical properties of the soils incorporated into the embankment within individual clasts of the natural soil (on a local scale) and a clear deterioration in the scale of the entire embankment, treated as the impact zone of building structures.

Keywords: CPTU, internal waste bank, constrained modulus, undrained shear strength

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1. Introduction

Lignite ("brown coal") mines in Central and Eastern Europe operate using open-pit mines, which have a significant impact on the environment. Massive lignite mining and the movement of significant amounts of overburden has attributed to large-scale transformations of the landscape: an external waste dump and an excavation are created below the original landform. The fact that open-pit mining has been systematically abandoned led to the implementation of various programs with the goal of reclaiming post-mining areas and giving them a "new life". In the Zagłębie Konińskie mines, located in central Poland, agricultural reclamation has been dominant until now. This was facilitated by the presence of glacial tills in the overburden. They are useful for both agricultural and forest reclamation due to their properties [1].

In addition to the traditional directions of forest and agricultural reclamation, new ones have emerged in recent years – water, recreational and economic reclamation [2]. The latter is associated with the need for intensive development of urban areas essential to the infrastructure of new branches of the local economy replacing coal mining. This creates the need to develop areas often characterized by weak geoengineering properties. One example of the use of post-mining areas in construction is the area around the city of Konin. The subsoil in this area is a chaotic mixture of preconsolidated clays, sands and tills, which are over 20-meter thick. The method of depositing the overburden often leads to clear differences in strength and strain characteristics when compared to similar soils formed as a result of geological processes [3].

Therefore, geotechnical soil analysis of the waste bank should be carried out with particular care. Therefore, the design of construction sites should be based on both laboratory and field tests with particular emphasis on the geological history of these soils.

Since there has been a significant increase in the use of post-mining lands for construction purposes, it seems reasonable to examine how the geotechnical properties of pre-consolidated soils can change as a result of the formation of a waste bank after several decades. In this article, in order to analyze the changes in the mechanical parameters of the external waste bank the results of in situ tests performed in the area of the former Gosławice open-pit mine were compared with the results of archival studies conducted in areas where glacial tills and silts occur naturally in the overburden of the exploited coal seam.

2. Characteristics of the tested man-made soils

The research was carried out on man-made embankment soils located in the southern part of the Niesłusz lignite open pit mine (Fig. 1), which is the oldest part of the Konin mining complex.

Originally, before the start of mining activities, the test site was dominated by quaternary formations dominated by glacial tills from the Weichselian and Riss glaciations. Near-surface sediments were represented by pre-consolidated compositions consisting of glacial tills, sands and silts. Clays with sand-gravel lenses, varved silts and erratics of the Weichselian

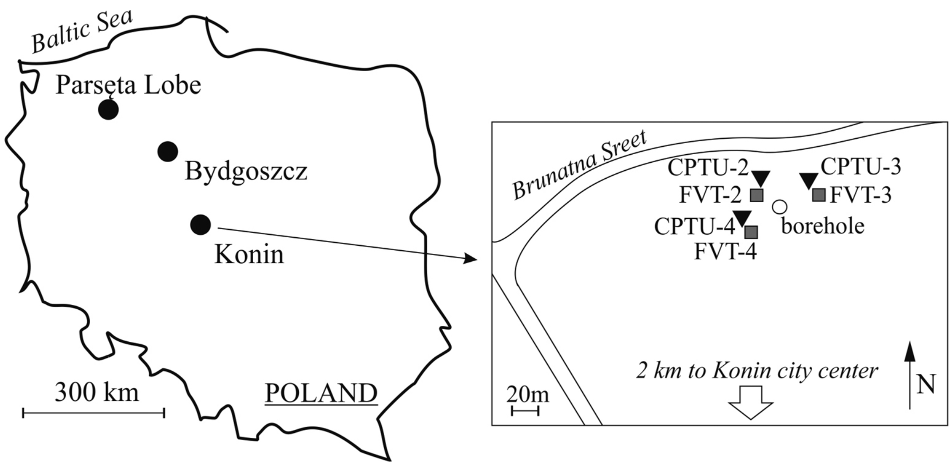

Fig. 1. Location of the test site (Konin) and archival research

and Warta glaciations lie on miopliocene formations, where lignite has been accumulated [4]. Silts with fragments of silty sands, sandy silts or fine-grained quartz sands lie directly above the coal [5].

Lignite deposits in the Niełusz open pit mine were exploited in the 1950s. The overburden of the Niesłusz open pit mine, the amount of which was estimated at 78 million m^3, was sent to the waste dump with self-unloading wagons, then by the excavator-pipeline-dumper system. The non-selective management of the overburden used by open-pit mining resulted in the natural material located on the waste dumps being a conglomerate of all the rocks present in the overburden. Thus, the macroscopic determinant for the studied man-made soils is the lack of uniformity. As far as samples taken for testing are concerned, this can be seen through "clusters" of darker material (Fig. 2). They are often relatively loosely arranged against the entire cores. They are distinguished by both colour and geotechnical properties of the soil.

Fig. 2. Sample for UU test from the core extracted from 9–9.5 m

The current geological structure of the near-surface zone, several to a dozen meters thick, is an embankment built predominantly from glacial till.

In the 1960s and 1970s, the post-exploitation areas were subjected to forest and agricultural reclamation in accordance with the trends of the time. The economic potential inherent in these areas was noticed in the 1990s, which led to the industrial development [3], [6].

3. Research methodology of man-made soils

The CPTU static penetration test, FVT rotary test (described in detail by Wierzbicki et al. [3]) and drilling were carried out in the waste dump, which allowed macroscopic analysis of the profile and sampling for laboratory tests (Fig. 1). Field tests were performed in accordance with ISO standards. To interpret their results in order to determine undrained shear strength (c_u) and the constrained modulus (M) the following formulas were used:

$$c_u = \frac{q_t - \sigma_{v0}}{N_{kt}} \tag{3.1}$$

where: q_t – corrected cone resistance [MPa] calculated according to ISO [7], σ_{v0} – overburden stress [MPa], N_{kt} – cone factor [–].

$$M = \alpha q_n \tag{3.2}$$

where: $q_n = (q_t - \sigma_{v0})$ – net cone resistance [MPa], α – empirical factor equal to 8.25 according to Mayne [8].

As part of the research, four quality class 1 core samples were collected using a Shelby sampler of 76 mm in diameter. Core samples were used for visual analysis of soil structure, compressibility in oedometer and shear strength in a triaxial compression apparatus.

Tests in the oedometer were performed in accordance with PN-EN ISO 17892-5 [9], using standard load levels in the Incremental Loading (IL) procedure: 25, 50, 100, 200 and 400 kPa. Based on the results of this study, the compressibility curves were determined and the secant constrained modulus in the complex stress ranges was determined.

Tests with the triaxial compression apparatus were carried out according to the unconsolidated and undrained (UU) test methodology [10] with cylindrical samples with diameter of 37 mm. The samples were tested in a deformation range of up to 20%, at shear rate of 1.5%/min. Based on the obtained results, the correlation between shear stress and deformation and undrained shear strength (c_u) were determined. Since not all the strength curves which were obtained indicated an exact moment of shear stress, the shear stress value recorded at the maximum deformation during the test was adopted as the value of c_u.

4. The results of archival research on the natural soils

To compare the geotechnical properties of the studied embankment soils we used the results of the research conducted on the natural soils. Their genesis and lithology correspond to soils of the overburden of lignite deposits accumulated on the waste bank. Due to the dominance of glacial clays and Pliocene silts in the embankment soils, the analysis used archival studies conducted in the Parsęta lobe [11, 12] and the Bydgoszcz area [13].

In the region of the Parsęta lobe, two levels of glacial clays of the older and younger phases of the Weichselian glaciation have been identified. Their geotechnical properties, although lithologicaly similar, are clearly different (Fig. 3 and 4). %

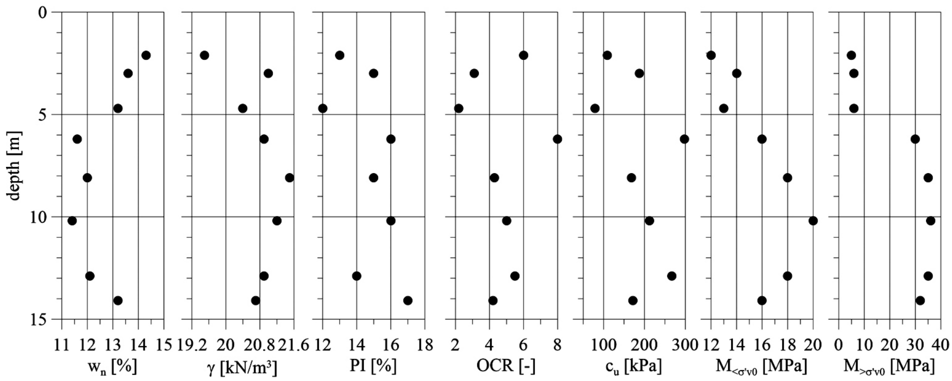

Fig. 3. Geotechnical properties of glacial till from the Parsęta lobe (based on laboratory tests Wierzbicki [11]): γ – soil unit weight, w_n – natural moisture, PI – plasticity index, OCR-overconsolidation ratio, c_u – undrained shear strength, $M_{<\sigma v}0$ – constrained modulus calculated for stress below overburden stress, $M_{>\sigma v}0$ – constrained modulus calculated for stress over overburden stress

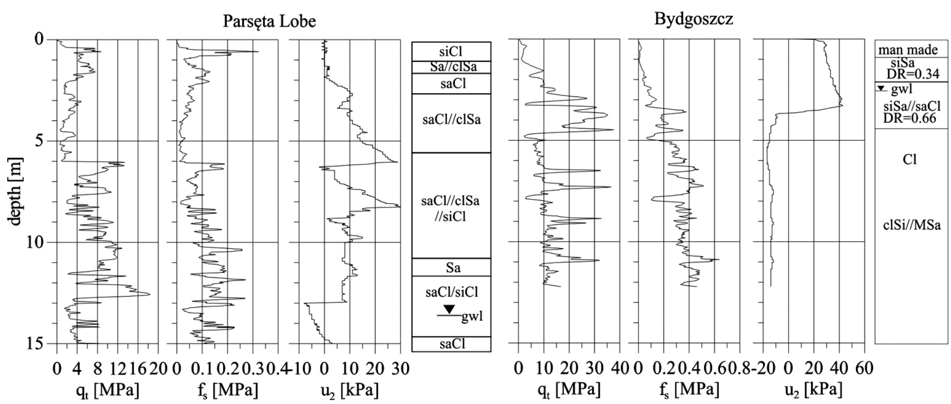

Fig. 4. Lithological profile and results of CPTU of glacial tills of the Parsęta lobe (based on Wierzbicki [11]) and Bydgoszcz (based on Młynarek et al. [13])

The existing diversity of sediments from different phases allows to observe the strain and strength characteristics of the soil in the profile with varying degrees of pre-consolidation. This allows a more comprehensive observation of changes in the characteristics of the soil after it is built into the embankment. Particular attention should be paid to the fact that there is a clear difference in the oedometric constrained modulus when it comes to the range of stresses exceeding the overburden stress σ'_{v0}. It indicates that the upper part of the profile can be treated as normally consolidated tailings and the lower part as pre-consolidated tailings. Similar differences, not as distinct though, can be found when analyzing the variability of undrained shear strength with depth.

For the tested soils, the comparison of results of in situ and laboratory tests made it possible to recommend the use of the factor α ranging from 8 to 13 (depending on the degree of pre-consolidation, Młynarek et al. [12]) to calculate the values of the constrained modulus from the CPTU and the value of the factor N_{kt} = 20 for younger soils and 25 for older soils to determine the undrained shear strength.

Archival studies of extremely consolidated silty clays found in the vicinity of Bydgoszcz were used in the case of Pliocene clays [13]. The soils found on the test site are covered with a 4-meter layer of sands and they are characterized by a strongly glacitectonically disturbed structure and numerous silty and sandy interlayers (Fig. 4 and 5).

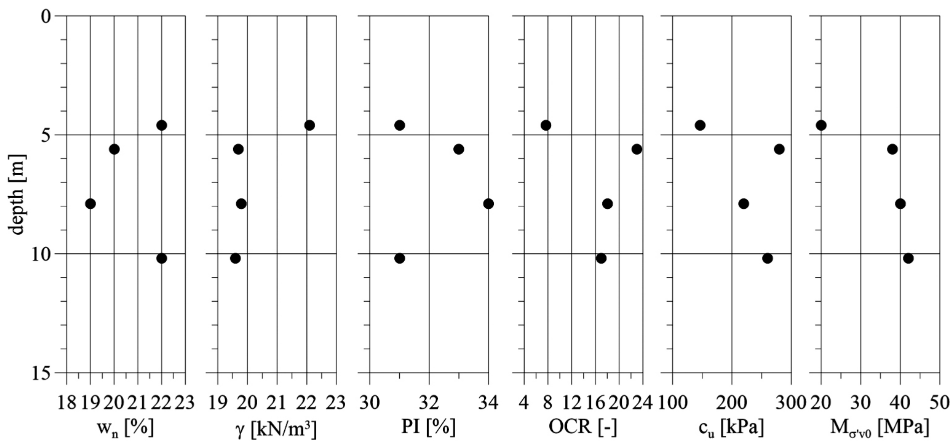

Fig. 5. Geotechnical properties of Pliocene clay from the Bydgoszcz region (based on Młynarek et al. [13]): γ – soil unit weight, w_n – natural moisture, PI – plasticity index, OCR-overconsolidation ratio, c_u – undrained shear strength, M – constrained modulus

The comparison of the results of laboratory tests and static testing of clays indicates the need to use unusual conversion factors when determining geotechnical parameters from CPTU. For undrained shear strength, the recommended value of N_{kt} is 25 and for the constrained modulus α equals 6.

5. Test results for the man-made soil

As mentioned earlier, the embankment soils of the internal waste dump are characterized by a unique structure. Structurally, they are a mixture of more or less merged clusters of different subsoils, from glacial clays to Pliocene clays (Fig. 2). The soils of the waste dump are highly diverse on a local scale (a dozen or so centimeters), however, as a result of the repeated process of formation of the embankment they are characterized by an "average" uniformity on a scale of several meters. This observation is confirmed by the results of the analysis of the basic physical properties of the soils in the profile: granulometric composition, natural moisture and unit weight (Fig. 6 and 7). Within a small depth range of the sampled test cores, there is a very high variability of these properties. It is also worth noting that, while in the case of granulometric composition and natural moisture this difference is present throughout the profile, it is smaller at great depths in the case of unit weight.

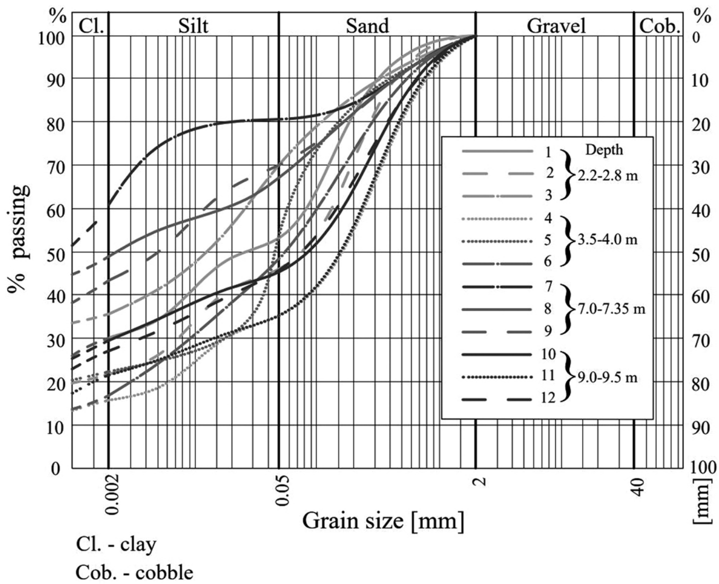

Fig. 6. Grain-size distribution curves of the soils from the internal waste bank

The results of the CPTU and FVT tests on man-made soils presented and discussed in more detail in the paper by Wierzbicki et al. [3], indicate that there is previously mentioned local variation in terms of the results. At the same time, they show that the trend of changes in results with depth is constant (Fig. 8).

Wierzbicki et al. [3] pointed out that by calculating undrained shear strength c_u on the basis of the CPTU (according to equation (3.1)), the N_{kt} factor equal 15 should be adopted for the soils found in the waste dump. The UU studies (Fig. 9), carried out as a part of the current research, made it possible to compare the results of in situ and laboratory tests with samples of intact structure. It is worth noting that despite conducting triaxial tests for very large deformations (20%), not all samples reached critical shear stress values.

Summary of c_u values obtained from in situ and laboratory tests indicate characteristic differences in the analyzed profile (Fig. 10). In its upper part, to approximately 4 m, the soil shows a significantly higher shear strength determined by the UU test than by the CPTU or FVT tests. This difference disappears with depth, so with an increase in overburden stress.

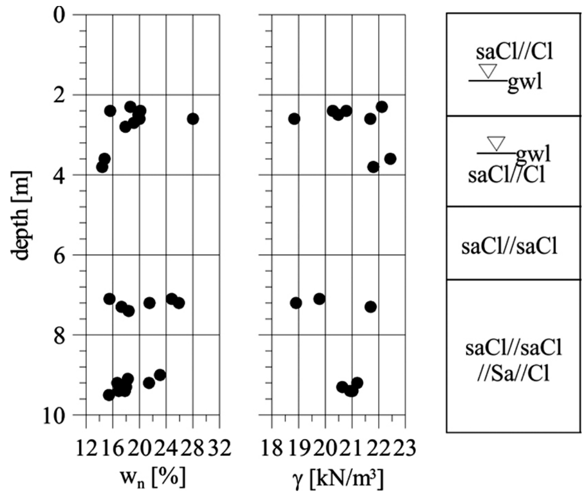

Fig. 7. Natural moisture w_n and soil unit weight γ of the soils found in of the waste dump

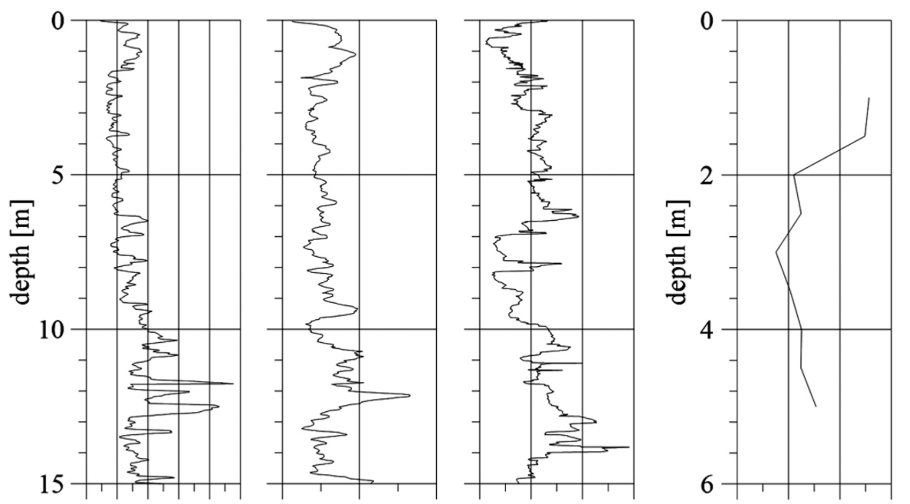

Fig. 8. Values of the corrected cone resistance q_t from the CPTU and shear strength c_u from the FVT test for soils from the internal waste dump (after Wierzbicki et al. [3])

Since most of the structures designed in the studied area generate stresses of 100–200 kPa at the foundation level, the constrained modulus of the embankment soils was determined in this stress range based on the IL test. In addition, the modulus values in the ranges of 50–100 kPa and 200–400 kPa were determined assuming that the lower range corresponds to the reaction of the subsoil in the initial phase of the construction and the higher one

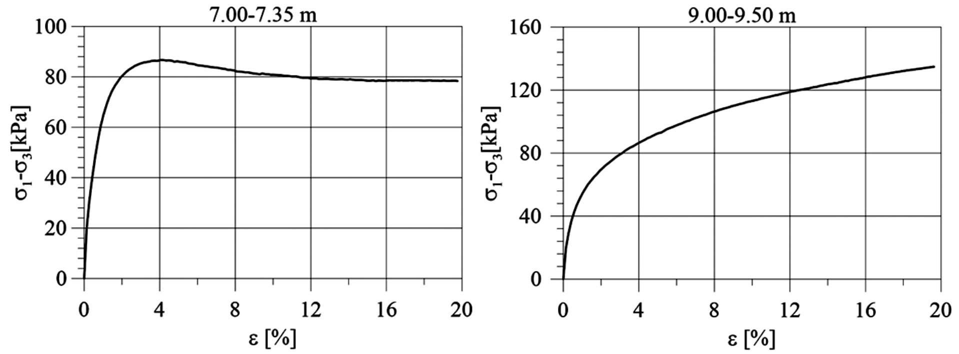

Fig. 9. Sample results of the UU test for internal waste dump soils

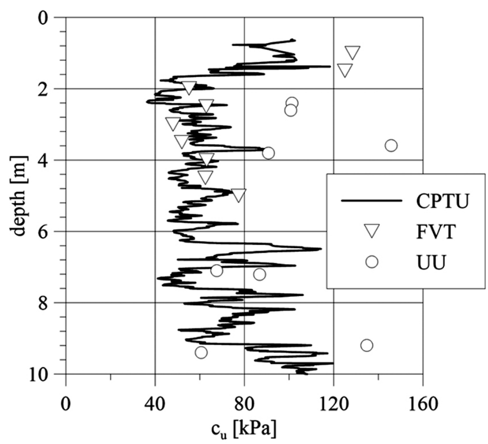

Fig. 10. Summary of values c_u determined by CPTU, FVT and UU tests in the test profile of the internal waste dump

corresponds to the values of the load-bearing capacity of the soil. In determining the constrained modulus based on the CPTU test, the formula (3.2) was used, initially using an average α value of 8.25 after Mayne [8] (Fig. 11).

The values of the constrained modulus M determined by the CPTU and the oedometric tests show an increase in values typical for normally consolidated sediments with depth. However, it is worth noting that the compatibility of the adopted factor α is particularly relevant to the results of oedometric tests in the highest stress range to a lesser extent in the intermediate range, and not at all in the lowest range. Importantly, the lack of compatibility does not result from the adoption of too low a value α (as suggested by Młynarek et al. [12] in the case of normally consolidated sediments), but from the fact that its value is too high (as indicated by Młynarek et al. [13] in the case of pre-consolidated sediments). It should be noted that the adoption of values $\alpha = 6$ (as in the case of the above-mentioned Pliocene silts) results in a very good match between the results of in situ tests and the constrained modulus in the range of stresses when the structure cooperates with the subsoil.

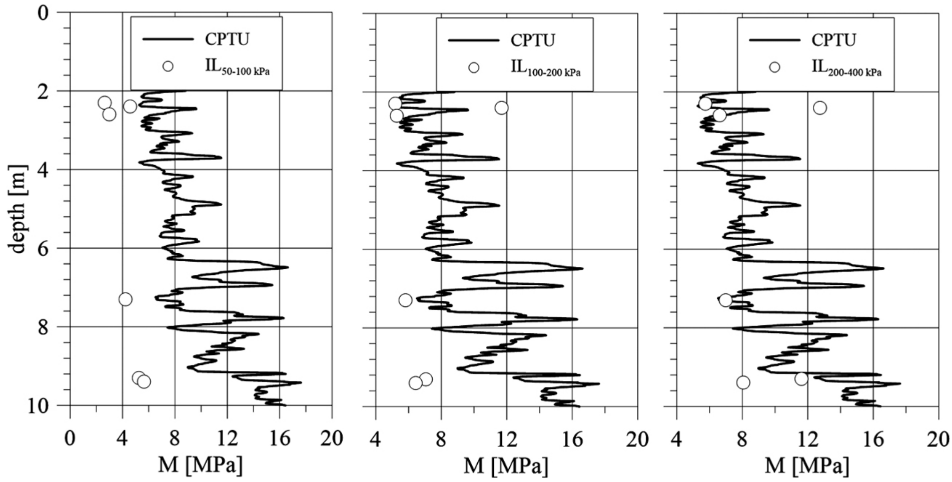

Fig. 11. Comparison of the constrained modulus value with laboratory and CPTU tests for soils found in the waste dump

6. Discussion

In order to compare the strength and strain properties of the natural soil and embankment soils, the undrained shear strength and the constrained modulus were normalized with the value of the overburden stress, according to the formulas (6.1) and (6.2).

$$\frac{c_u}{\sigma'_{v0}} = \text{normalized undrained shear strength} \tag{6.1}$$

$$m = \frac{M}{p_a \left(\dfrac{\sigma'_{v0}}{p_a}\right)^{1-a}} \tag{6.2}$$

where: c_u – undrained shear strength, m – modulus ratio, M – constrained modulus, p_a – atmospheric pressure, a – empirical coefficient assumed = 1, σ'_{v0} – overburden stress.

Summary of values c_u/σ'_{v0} makes it possible to note that although the lithology corresponds largely to the Pliocene clays, the waste dump soils cannot be considered as strongly consolidated sediments (Fig. 12). The process of extraction from the deposit, fragmentation, transport and re-deposition has irrevocably changed the unique properties of the subsoil. A similar observation applies to the strongly over-consolidated top part of the older glacial till of the Poznań phase of the Weichselian glaciation (about 6–7 m bgl). Ambiguous results are obtained by comparing layers of the embankment soils (up to 4 m bgl) with the results obtained from glacial tills of the Pomeranian phase. In this case, laboratory tests performed in both subsoil and embankment soils are very similar to the results of the CPTU test performed in the subsoil. However, they clearly differ from the result of in situ tests conducted for embankment soils. This observation leads to the conclusion that in the case of younger soils a small laboratory sample and a local scale, the strength characteristics of the soil do not undergo significant degradation. However, if they are analyzed on a larger scale and they correspond to in situ conditions, they show some deterioration of these properties. Also, a comparison with the local and small-scale effect of the pre-consolidation effect present in younger glacial tills found in the zone right above the ground seems to confirm the partial preservation of the influence of the former stress in the embankment soil clusters.

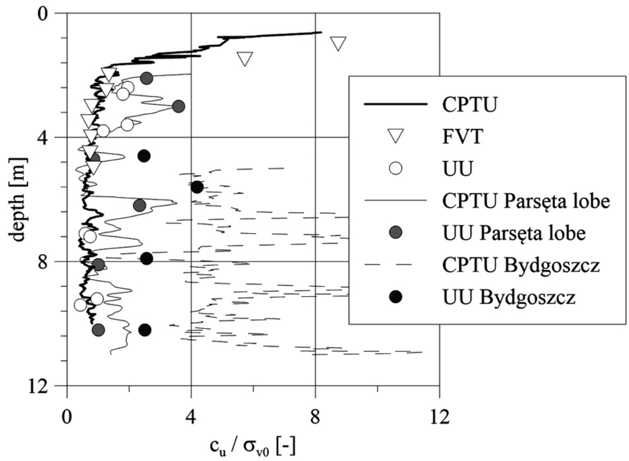

Fig. 12. Compilation of normalized undrained shear strength values in waste dump soils and glacial clays and Pliocene clays determined by various methods

The analysis of changes in the constrained modulus in the profile leads to similar conclusions. After normalizing its values (obtained in the reading range of 100–200 kPa), the value of the dimensionless factor of the embankment soils modulus is almost uniform with the depth (Fig. 13). There is also a great similarity between the values obtained from in situ and laboratory tests.

On the other hand, in the case of glacial clay of the Pomeranian phase, the laboratory test shows a significantly lower compressibility than in the case of redeposited soils from the waste dump.

This correlation is slightly different in the reading stress range of 200–400 kPa (in embankment soils) and above the primary stress (in relation to the subsoil) (Fig. 14). In this case, the clays of the Pomeranian phase have a similar compressibility to embankment clays, and the clays of the Poznan phase are less similar in their compressibility.

The observed regularities indicate a different effect of soil redeposition on its compressibility depending on the history of the subsoil stress and the range within which the compressibility is determined.

Regardless of the above observations, CPTU tests performed in both glacial clays and Pliocene clays indicate a significantly lower compressibility of the subsoil than of an embankment soil.

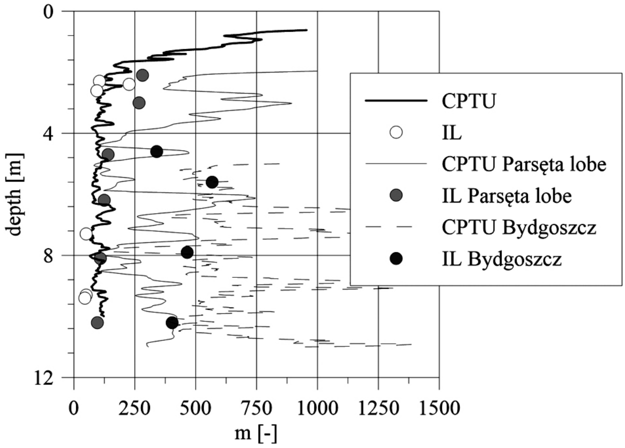

Fig. 13. Comparison of the values obtained for the modulus dimensionless factor determined by the CPTU and oedometric tests in the range of 100–200 kPa in waste dump soils, glacial clays (below the overburden stress) and Pliocene clays

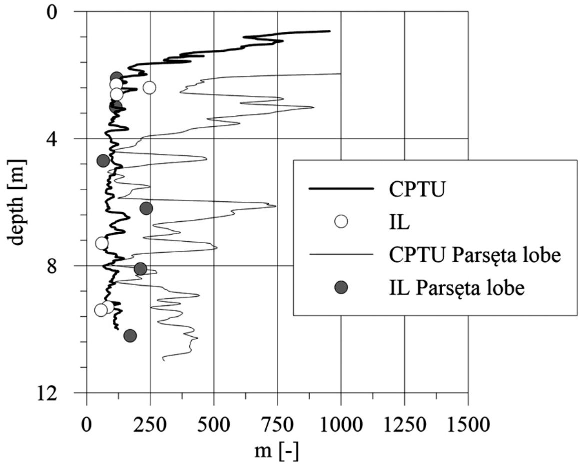

Fig. 14. Comparison of the values obtained for the modulus dimensionless factor determined from the CPTU and oedometric tests in the range of 200–400 kPa in waste dump soils, glacial clays (above the overburden stress) and Pliocene clays

7. Summary and conclusions

It can be concluded that the deterioration of the strength and strain properties of the studied soils as a result of their disconnection, transport and dumping is not a homogeneous process and does not occur regardless of the geological history of the subsoil and the scale of impact the structures have on the subsoil.

In strongly consolidated soils, the loss of rigidity is significant and in the full range of stress. Slightly over-consolidated or normally consolidated soils show a significant loss of rigidity only in the range of stresses lower than σ_{v0}, or 200 kPa. In turn, strain properties in the range of higher stresses (above 200 kPa) for pre-consolidated soils and soils from older glaciations deteriorate.

In the case of strength characteristics, an interesting feature of the tested embankment soils is an observably smaller reduction in undrained shear strength on a local scale, a small sample of soil, as compared to the scale of the entire foundation subsoil.

When analyzing the foundation on the soils of an internal waste dump, it is necessary to distinguish between the interpretation of the test results in the near-surface zone (up to about 4 m depth) and deeper, and adjust the interpretation methods to the expected range of stresses from the structure.

Acknowledgements

This article has been prepared using funds allocated for individual support of research projects of the Faculty of Geographical and Geological Sciences of Adam Mickiewicz University in 2022.

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Właściwości mechaniczne gruntów zwałowiska wewnętrznego kopalni węgla brunatnego a ich cechy pierwotne

Słowa kluczowe: CPTU, zwałowisko wewnętrzne, ściśliwość, wytrzymałość na ścinanie bez odpływu

Streszczenie:

Współczesny rozwój obszarów miejskich związany jest m.in. z lokalizacją obiektów przemysłowych na obrzeżach miast. Coraz częściej budynki komercyjne posadawiane są na terenach dotychczas niewykorzystywanych pod budownictwo. Do takich obszarów należą m.in. zrekultywowane hałdy kopalni węgla brunatnego w rejonie konińskim. Zwałowany grunt jest chaotyczną mieszaniną fragmentów glin polodowcowych i iłów plioceńskich, często przekraczającą 20 m miąższości, która z czasem ulega naturalnej konsolidacji. Sposób powstawania zwałowiska powoduje, że mimo iż hałdy wykonane są z gruntu naturalnego, ich charakterystyka wytrzymałościowa i odkształceniowa wyraźnie odbiega od tej, charakterystycznej dla podobnych litologicznie gruntów deponowanych w wyniku procesów geologicznych. W takim przypadku zastosowanie standardowego podejścia badawczego może spowodować przeszacowanie wytrzymałości i sztywności gruntu. Ze względu na złożoną strukturę zwałowiska do rozpoznania geotechnicznego wykorzystano badania in situ: CPTU i FVT oraz badania laboratoryjne w aparacie trójosiowego ściskania i edometrze. Wyniki porównano z rezultatami badań prowadzonych w podobnych gruntach zdeponowanych naturalnie. Uzyskane wyniki dają cenną charakterystykę geotechniczną gruntu nasypowego, który w swoich dużych fragmentach zbudowany jest z klastów gruntu naturalnego. Uzyskane wyniki wskazują na stosunkowo niewielką zmianę właściwości geotechnicznych gruntów inkorporowanych w zwałowisko w obrębie poszczególnych klastów gruntu rodzimego (w skali lokalnej) i wyraźne ich pogorszenie w skali całego zwałowiska, traktowanego jako strefa oddziaływania obiektów budowlanych.

Received: 2023-05-08, Revised: 2023-06-16