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PHYSICAL AND MECHANICAL PROPERTIES OF MODIFIED SOILS USED AS A MATERIAL FOR EARTHWORKS, BASED ON SEDIMENTS FROM THE AREA OF ROŻNOWSKIE LAKE

WŁAŚCIWOŚCI FIZYCZNE I MECHANICZNE GRUNTÓW PRZEROBIONYCH, STOSOWANYCH JAKO MATERIAŁ DO FORMOWANIA BUDOWLI ZIEMNYCH ZNAJDUJĄCYCH SIĘ W REJONIE JEZIORA ROŻNOWSKIEGO

A b s t r a c t

This paper presents a detailed overview of selected physical and mechanical properties of cohesive soils deposited the Rożnowskie Lake and the possibility of using these sediments in the construction of earth structures. The scope of the article includes a brief description of processes related to the sedimentation of argillaceous sludge in Rożnowskie Lake.

Keywords: *earth structures*, *embankments*, *modified cohesive soils*, *Rożnowskie Lake*

S t r e s z c z e n i e

Artykuł przedstawia szczegółowy przegląd wybranych właściwości fizycznych i mechanicznych gruntów spoistych zdeponowanych w Jeziorze Rożnowskim oraz możliwość wykorzystania tych osadów w konstrukcji budowli ziemnych. Zakres artykułu obejmuje również krótki opis procesów związanych z sedymentacji osadów ilastych w Jeziorze Rożnowskim.

Słowa kluczowe: *konstrukcje ziemne*, *nasypy*, *przerobione grunty spoiste*, *Jezioro Rożnowskie*

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1. Introduction

Several dams with a height of over 15 m. were built in Poland in the twentieth century. One of the biggest is the dam in Rożnów, which was completed in 1941. This dam is made of concrete and has a height of 15 m. The lake behind the dam has the following dimensions: depth- 49 m, total capacity – 228, 7 million cubic meters area – 1 776 ha, length – 22 km, maximum width – 1.5 km, and depth at the dam – 35 m; the catchment area of the dam is 4 883 km^2 [7]. The main purposes of the Rożnowskie Lake are electricity generation and flood prevention. The dam is a natural barrier to mineral material transported by the river in large quantities, especially at times of flood. As a result of these phenomena, which occur extensively in lakes of mountain rivers, the process of silting has spread. This is a big problem because it negatively affects the capacity for retention, which in turn translates into the longevity of the reservoir. Detailed information on this subject can be found, inter alia, in [2, 3, 8, 12–15, 17]. Analysis of the siltation of reservoirs in the upper basin of the Vistula River, showed that the average annual load within these reservoirs is 0.052–1.359 million m^3/year, and much sludge is accumulated in the Rożnowskie Lake [17]. Comprehensive studies conducted in the 1990s showed that the volume of accumulated material, particularly in the backwater area, can account for approximately 25% of the total capacity, ie approx. 50 million m^3 of sludge [20]. The large extent and significance of siltation of Lake Rożnowskie motivated the author to carry out experimental studies aimed at identifying and evaluating the properties of the deposited soil material and at providing an indication of the possibility of using these deposits, for example, in civil engineering.

2. Choice of soil material used to create earth structures

Guidelines for the selection of soil material for constructing earthworks can be found in various publications and industry standards, including in positions [4, 9, 10, 16, 19]. Soils used for the construction of embankments should have the following properties:
- particle size,
- compactibility,
- plasticity,
- cohesion,
- content of organic matter,
- chemical aggressiveness,
- the presence of water-soluble compounds,
- sensitivity to changes in volume (swelling and collapsing)
- resistance to weathering.

Some of these features are important, and some may be omitted, depending on the construction of the embankments and the specifics of the land, the choice of material for the construction of embankments is dependent on its future purpose.

The best natural soils used for forming embankments are cobbles, gravel, sand and loamy sands. In contrast, in dry soil (without access to ground, capillary and flowing water) the following can be used:

– pebbles of rocks such as marl, limestone, shale,
– silt and silty sands,
– clay, but not for high embankments,
– loess.

The following should not be used to make embankments:
– swelling soil,
– silts and clays with a liquid limit of more than 65%,
– peat and soil with additives soluble in water,
– soil with a bulk density less than 1600 kg/m^3,
– contaminated soil.

Some soil can be used for the construction of embankments, but only after appropriate modification or enhancement by means of additional binders such as cement, lime, active ashes, etc.

An important element in the construction of embankments is an appropriate density, which ensures a stable structure, which will not succumb to rapid degradation. It is expressed by the density index I_s. Its value, typically in the range 0.90–1.0, should be determined according to the type of building, type of soil and place of incorporation in the embankment. Natural soil moisture W_n during its compaction should be close to the optimum moisture content W_{opt}. It is recommended that: $W_n = W_{opt} \pm 2\%$ – for cohesive soils except sandy gravel, gravel and clayey gravel, for which $W_n \geq 0.7\ W_{opt}$. If the cohesive soils have a natural moisture content significantly greater than W_{opt}, they should be dried on the side before being incorporated into the embankment.

3. Description and results of field and laboratory studies

The sampling of bottom sediments collected in the Rożnowskie Lake was preceded by a thorough analysis of archival research. Most of the information on the distribution and nature of the deposited sediments was provided by a study carried out in 1994 by the Polish Geological Institute [20]. At that time, twenty-three drilling tests were carried out at a spacing of 500 × 500 m. The sampling interval was 1.0 m (±0.2 m). The samples were then wet sieved through a set of sieves of 0.2; 1.0; 2.0 mm. The research found that the maximum thickness of the sludge accumulated in Lake Rożnowskie was approx. 6 m. These deposits are located in the central part of the lake and come from along the old bed of the Dunajec River. Towards the edges, sediment thickness decreases – the average thickness there is 3.5 m ± 0.9 m.

It was found that at the bottom of the lake there are mainly silt and clay sediments and a further admixture of sand. The soil has a layered structure and a colour from dark to light grey. The vertical and horizontal distribution is characterised by high homogeneity. The median sediment grain composition is as follows; particles smaller than 0.2 mm – 79.0%, particles from 0.2 to 1.0 mm – 19.7%, particles from 1.0 to 2.0 mm – 0.7% and particles larger than 2.0 mm – 0.6%.

From 2001–2005, the author made field and laboratory studies of sediment found at the bottom of Lake Rożnowski in the Tęgoborzy region and Holocene alluvial flood deposits soil on the lowest terrace of the river Dunajec, in the region of Kurów and Nowy Sącz

(Fig. 6). The scope of laboratory tests included macroscopic analysis, grain size analysis, mineral composition, moisture content, organic matter content, bulk density, plastic limit, liquid limit, optimum moisture content, permeability coefficient, oedometer compressibility modulus and shear strength.

4. Characteristics of physical and mechanical properties of sediments

4.1. Types of soil and their physical properties

Analysis of the results of the granulometric composition and some of the physical properties showed that the sediments of the Rożnowskie Lake and primary alluvial of the Dunajec river consist of specific types of soil:

– Holocene alluvial of the Dunajec River (Type 1) – silt, sandy silt, and clayey silt. The proportion of clay fraction is from 8 to 13% and the content of organic matter is from 0.7 to 1.6%. They are characterized by a high degree of decomposition of organic matter, the calcium carbonate content being below 1%. The plastic limit is in the range of 19.0–23.6%, the liquid limit value is 30.1–37.0%, and the plasticity index is 10.3–13.6.
– Sediments from the bottom of the Rożnowskie Lake – silt, sandy silt, clayey silt and silty clay. The proportion of clay fraction is from 8 to 19% and the content of organic matter is from 0.8 to 2.9%. Sludges have a low degree of decomposition of organic matter, the content of calcium carbonate being less than 1%. The plastic limit is in the range of 20.0–28.6%, the liquid limit value is 41.6–49.5%, and the plasticity index is 17.5–22.0. Within the bottom sediments, two types of soil were isolated: Type 2 – silt, sandy silt and Type 3 – clayey silt, silty clay (Fig. 1).

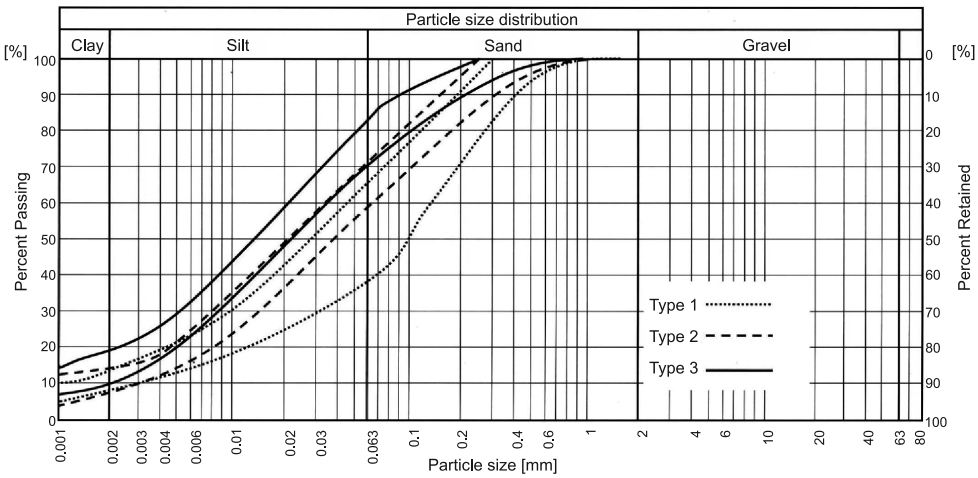

Fig. 1. Particle size distribution chart of tested sediments

4.2. Optimum moisture and maximum bulk density of soil

The soil optimum moisture W_{opt} is a very important property determined for materials used in the construction of embankments. By controlling this property, one can obtain the highest density of soil as expressed by the maximum bulk density of soil ρ_{ds}. Determination of these quantities is made in the laboratory according to the Proctor method. For the study, approximately 30 kg each of the three types of soil were sampled, they were then air-dried, crushed, mixed well and between 6 and 10 tests of optimum moisture for each type of soil were carried out. Analysis of the samples yielded the following results:

- Type 1 – inorganic silt and clayey silt, optimal moisture W_{opt} = 15.4–18.0% averaging 16.4%, maximum bulk density of soil ρ_{ds} = 1.70–1.77 [g/cm^3] with an average of 1.75 [g/cm^3], total porosity n = 0.33–0.36 an average of 0.34, void ratio e = 0.51–0.56 an average of 0.52, degree of moisture S_r = 0.82–0.85 with an average of 0.84 and a full saturation moisture W_{NS} = 18.8-21.1% averaging 19.6%.
- Type 2 – low-organic silt and clayey silt, optimal moisture W_{opt} = 19.8–22.4% averaging 20.8%, maximum bulk density of soil ρ_{ds} = 1.57–1.63 [g/cm^3] with an average of 1.61 [g/cm^3], total porosity n = 0.37–0.40 with an average of 0.39, void ratio e = 0.60–0.67 with an average of 0.63, degree of moisture S_r = 0.85–0.88 with an average of 0.87 and a full saturation moisture W_{NS} = 23.2–25.5% with an average of 23.9%.
- Type 3 – organic silty clay, optimum moisture W_{opt} = 23.2–25.0% averaging 24.4%, maximum bulk density of soil ρ_{ds} = 1.51–1.57 [g/cm^3] with an average of 1.54 [g/cm^3], total porosity n = 0.40–0.42 with an average of 0.41, void ratio e = 0.67–0.74 with an average of 0.70, degree of moisture S_r = 0.89–0.91 with an average of 0.90, and a full saturation moisture W_{NS} = 25.5–28.1% averaging 26.8%.

These studies allow the determination of the density index I_s, the value of which is most often from 0.90 to 1. The value of the density index equal to 1 for cohesive soils can be very difficult to achieve without additional modification. The value of about 0.95–0.97 is sufficient in many cases, for example, in hydraulic engineering constructions it is sufficient for objects of class I [19], while for road embankments, it is sufficient for the lower parts of the embankment below the freezing zone [10]. With this in mind, the study of the mechanical properties of soil was made for modified samples which had been prepared for optimum moisture and density index $I_s \geq 0.95$.

4.3. Coefficient of permeability

Laboratory tests were performed for the permeability coefficient in an oedometer. The experiment was performed with a variable hydraulic gradient in the range of 5 to 50. The study was performed on samples of the optimum moisture, density index I_s = 0.92; 0.95; 0.98; 1, a diameter of 65 mm and a height of 20 mm. The resulting values for the studied soil are shown in Fig. 2. Analysis of the results shows a clear decrease in the value of the coefficient of permeability with an increasing of the density index. For samples with a density index of 0.95, the average values of the permeability coefficient are: 9.14×10^{-9} m/s (Type 1), 2.68×10^{-9} (Type 2) and 6.08×10^{-10} (Type 3). The lowest, and therefore the most favorable results were obtained in the case of soil Type 3, which is probably associated with the highest content of clay minerals. Soil Type 1 has the highest value of permeability coefficient, about

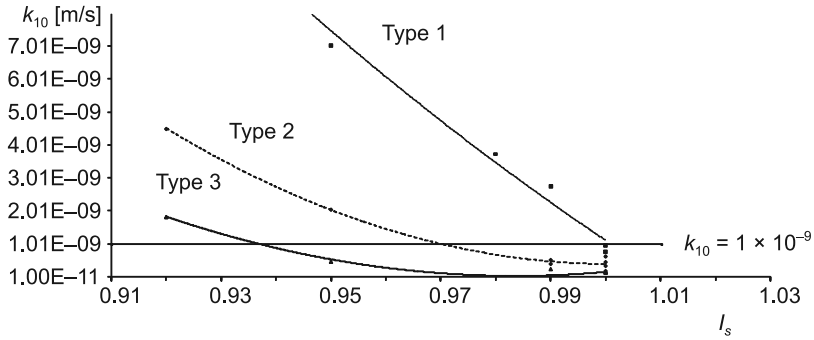

Fig. 2. The relationship between permeability coefficient k_{10} and density index I_s in the oedometer test

2–3 times higher than soil Type 3. Soil Type 2 obtained intermediate values. A detailed analysis of this issue is also given in the articles [5, 6].

4.4. Swell index

Investigating swelling is of great importance in the analysis of soil materials used to form the substrate of hydraulic structures, roads, airports, etc. The process of swelling is characteristic of cohesive soils and depends on the percentage content and mineral composition of the clay fraction in addition to the presence of organic matter [11]. The biggest influence on the properties of swelling is the presence of montmorillonite minerals.

X-ray studies conducted on the bottom sediments of Lake Rożnowskie showed that the mineral composition is mainly quartz, clay minerals, and additionally calcite, anhydrite and muscovite. The clay minerals are illite and kaolinite. Trace amounts of calcium montmorillonite were also found.

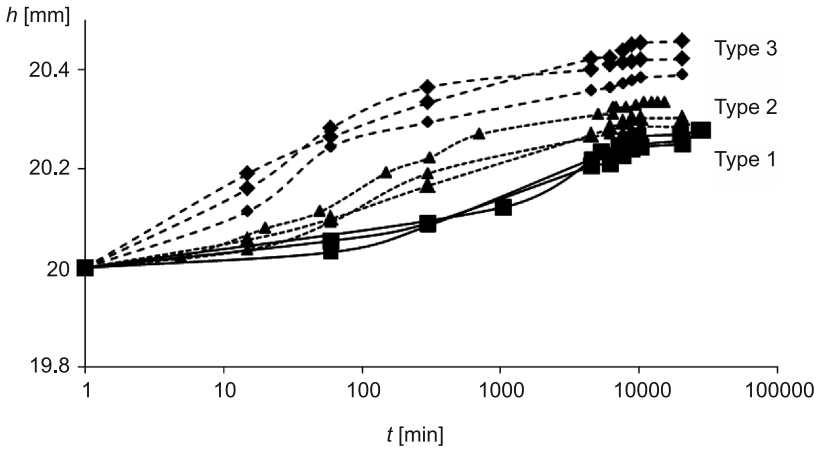

Fig. 3. Graph showing change in height of samples during the study in the swelling test

The test of the properties of swelling was performed for samples representing three types of soil. The tests were performed on samples of optimum moisture, density index $I_s \geq 0.95$, having a diameter of 65 mm and a height of 20 mm. Analysis of the results showed that soil Type 3 has the highest value of the swell index, in the range of 1.70 to 2.0% and averaging 1.8%. Soil Type 1 received the lowest value, in the range of 0.91 to 1.12% with an average of 1.02%. Soil Type 2 obtained intermediate values of the swell index, in the range of 1.63 to 1.78% with an average of 1.71. It is found that the swelling ratio is a low value, which is probably the result of a small presence of montmorillonite and a slight presence of organic matter. Value of the swelling pressure is less than 12.5 kPa.

4.5. Modulus of compressibility

Compressibility studies were performed under laboratory conditions in an oedometer. The study involved samples representative of the three types of soil. The tests were performed on samples of optimum moisture, density index $I_s \geq 0.95$, with a diameter of 65 mm and a height of 20 mm. The compressibility of the soil was measured by determining the oedometer compressibility primary modulus M_0 and secondary modulus M in the range of 0 to 400 kPa.

Analysis of the results (Tab. 1) showed that soil Type 1 is characterized by the highest value of primary and secondary compressibility modulus, while the soils Type 2 and Type 3 obtained lower values. The biggest difference is obtained at a load of 400 kPa. Primary compressibility modulus M_0 obtained for soil Type 1 is about 60% higher compared to the sediment Type 3 while the secondary modulus is about 30% higher. The presence of organic matter in the studied soils has a significant influence on the results – even a small amount causes high compressibility.

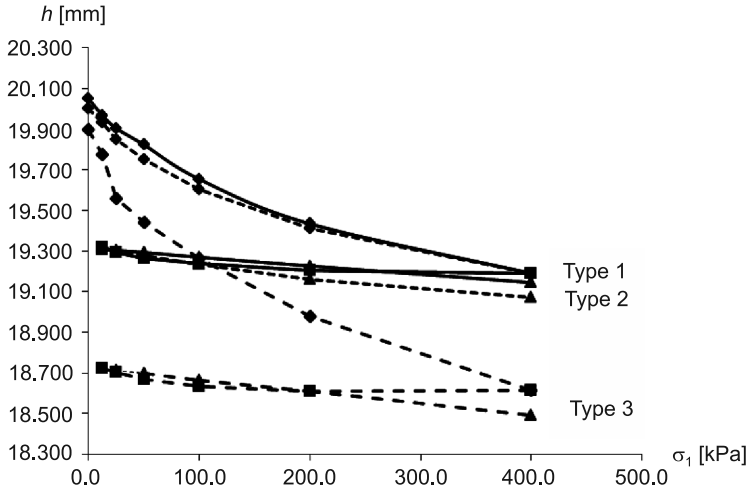

Fig. 4. The relationship $h = f(\sigma_1)$ for the oedometer compression tests

Table 1

Summary test results of oedometer compressibility modulus of soil

Oedometer compressibility modulus; primary (M_0) and secondary (M) in kPa.			
	Type 1	**Type 2**	**Type 3**
$M_{0\,(0–12.5)}$	3542	2384	1440
$M_{0\,(12.5–25)}$	3254	4200	1194
$M_{0\,(25–50)}$	4999	6166	3947
$M_{0\,(50–100)}$	6254	6319	5992
$M_{0\,(100–200)}$	9618	9287	7970
$M_{0\,(200–400)}$	17 196	16 026	10 561
$M_{(12.5–25)}$	52 435	20 746	23 352
$M_{(25–50)}$	50 293	23 130	26 205
$M_{(50–100)}$	39 701	22 964	23 859
$M_{(100–200)}$	46 184	29 875	30 097
$M_{(200–400)}$	49 044	42 361	32 761

4.6. Angle of effective internal friction ϕ'

The angle of effective internal friction ϕ' was made for three types of soil using the triaxial compression test (CID – consolidated isotropic drained).

The interpretation of test results was carried out using the theory of Columba-Mohr specified for values of the effective stress [1]. It was also recognised that the effective cohesion c' is close to 0 kPa, which is its value for the modified soil (Fig. 5).

Analysis of the results showed that the highest value of the effective friction angle was for Type 1 soil where $\phi' = 32.4°$, for Type 2 soil – $\phi' = 31.6°$, and for Type 3 soil – $\phi' = 31.2°$.

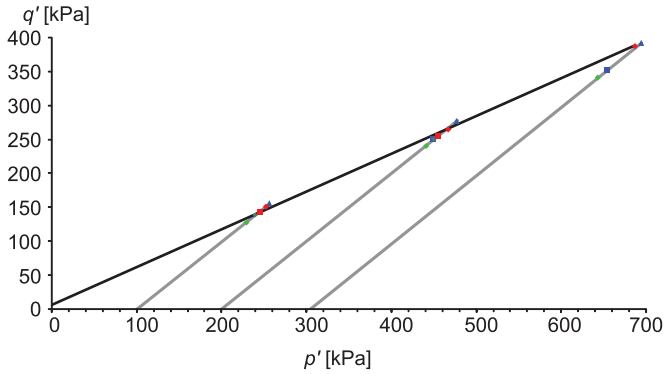

Fig. 5. The relationship $q' = f(p')$ for the triaxial compression tests

In general, it must be recognised that effective measurements obtained are high. The content of 2–3% of organic matter in the soil does not significantly affect the value of the effective friction angle.

5. Assessment of the suitability of sludge as a material for the construction of earth structures

Table 2 presents the guidelines for the soils used for the construction of embankments. It also presents the results obtained for the studied sediments. Analysis of the results showed that the Holocene alluvial of the Dunajec River satisfied all the criteria for the tested soil. Sediments from the bottom of the Rożnowskie Lake also meet the recommended requirements except with regard to the maximum density of soil. The guidelines recommend that $\rho_{ds} > 1.6$ g/cm^3, the results of laboratory tests were in the range of 1.51 to 1.63 g/cm^3, averaging 1.57 g/cm^3. This mainly applies to deposits of organic clay (Type 3). The discrepancies obtained for these deposits can be considered as small. Sediments of organic content less than 2% (silty clay and sandy silt – Type 2) meet the required criteria.

Table 2

Summary of criterion values of geotechnical parameters for the analysed sediments

Parameters	Units	Required parameters [9, 19]	Sediments of the Rożnowskie Lake		Sediments of the Dunajec River	
			Values	Average values	Values	Average values
Clay fraction *fi*	%	> 30	8–19	12	7–13	10
Liquid limit W_L	%	> 65	41.6–49.5	45.7	30.1–37.0	32.6
Content of $CaCO_3$	%	–	< 1%	–	< 1%	–
Organic matter I_{om}	%	> 3	0.80–2.89	1.83	0.72–1.61	1.12
Content of gypsum and soluble salts	%	> 3	–	–	–	–
Maximum bulk density ρ_{ds}	g/cm^3	< 1.6	1.51–1.63	1.57	1.70–1.77	1.75

6. Summary and conclusions

1. The article presents the results of geotechnical properties of cohesive sediments deposited in the Rożnowskie Lake and in the floodplain terraces of the Dunajec River;
2. The Dunajec River soils are silt, sandy silt, and clayey silt with an organic matter content of 0.7 to 1.6%. Sediments from the bottom of the Rożnowskie Lake are silt, sandy silt, clayey silt and silty clay. The content of organic matter is between 0.8 and 2.9%;
3. For samples with a density index of 0.95, the average values of the permeability coefficient are: 9.14×10^{-9} m/s (for the Dunajec River) and 6.08×10^{-10} m/s (for the Rożnowskie Lake);

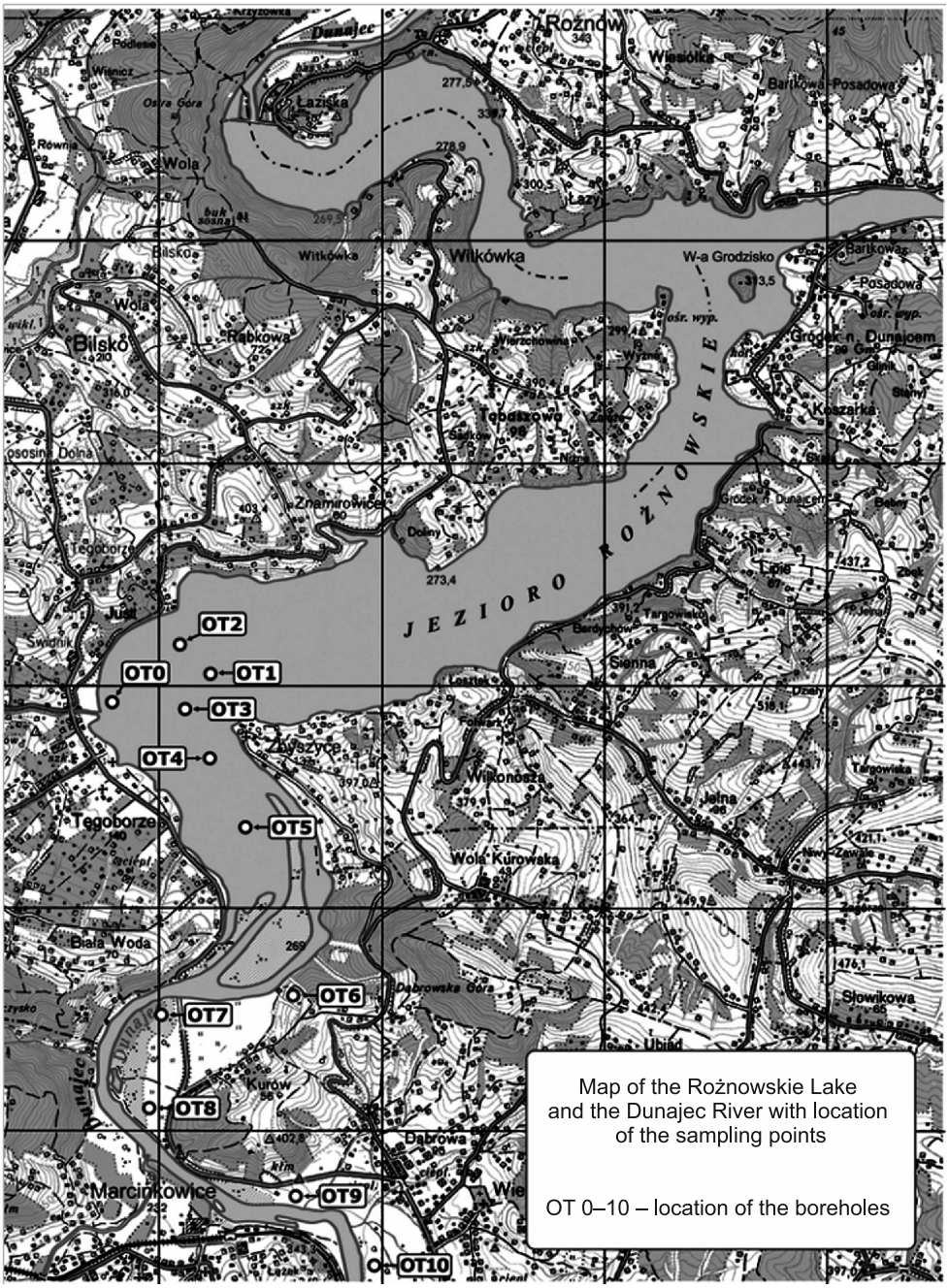

Fig. 6. The map of the Rożnowskie Lake and the Dunajec River with the sampling points indicated [18]

4. Investigation of swelling showed that the swelling ratio had a low value in the range of 1.7 to 2.0%, which is probably the result of a small amount of montmorillonite and the slight presence of organic matter;
5. The primary and secondary compressibility modulus for the Dunajec River is higher than for sludge from the Rożnowskie Lake by between 30 and 60%;
6. The effective friction angle has a high value, between 32.4° and 31.2°. The effective cohesion is close to 0 [kPa], which is characteristic for modified soil;
7. Sediments from the Rożnowskie Lake and the Dunajec River can be used as a material for construction of earth structures.

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