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# Usability evaluation of bottom sediments from Czorsztyn–Niedzica reservoir backwater in geotechnical engineering

**Andrzej Gruchot,**

**Karolina Sudyka**

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The paper presents the geotechnical characteristics and heavy metal contents in bottom sediments of the Czorsztyn–Niedzica reservoir backwater and the evaluation of their usability for geotechnical engineering. The bottom sediments were classified as cohesive humus silts and the soils below that depth as non-cohesive (silty and medium sands). The analysis of cadmium, zinc and lead content showed a low concentration of these metals in the sediments on the geotechnical background level. Only copper content showed an increased concentration, but it did not exceed the class II of sediment purity. The tested sediments did not fulfil most of the required criteria and thus they rather cannot be used for geotechnical engineering purposes. However, in case of sediment extraction, there is a possibility of improving their granulation or stabilization with a hydraulic binding agent.

**Key words:** bottom sediments, reservoirs, usability evaluation, heavy metal contents, geotechnical characteristics

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**Andrzej Gruchot.** Department of Hydraulic Engineering and Geotechnics, University of Agriculture, al. Mickiewicza 24/28, 30-059 Kraków, Poland. E-mail: rmgrucho@cyf-kr.edu.pl

## INTRODUCTION

Siltation of a water reservoir is defined as a complex of the morphological processes that lead to a gradual reduction of its capacity (Rzętała, 2003). This process includes accumulation of material from abrasion of the reservoir banks, necrosis of plants and mostly the accumulation of sediments transported by side streams. Retaining of fluvial sediment causes a series of negative effects and hinders the proper functioning of a reservoir. In the majority of reservoirs, siltation is a long-lasting process; at the earliest, operation difficulties may appear in backwater in which larger particles begin to sediment.

Therefore, when planning and operating water reservoirs, a proper recognition of the siltation process and consideration of its effects, such as a decrease of usable capacity, is essential. In existing reservoirs, recognition of sediment characteristics, both geotechnical and chemical, can be helpful and allow making decisions as to the possible extraction of sediments and putting them to use. In particular, the issue of using sediments in geotechnical engineering is worth considering.

Among the methods used for the estimation of bottom sediment mass and sedimentation rate, analytical and measuring methods can be distinguished (Bogucka, Magnuszewski, 2006; Juracek, 2006; Jakubauskas, deNoyelles, 2008). Analytical methods are mostly based on a balance of the material that is transported by a river; rarely, the Universal Soil Loss Equation is used, whereas measuring methods are based on repeated surveys of reservoir bowls, with the use of newer and newer techniques ranging from the classic geodesic surveys and echo sounders with range-finder for areas below water level up to a GPS system. By comparison of bathymetric maps from consecutive surveys carried out in the course of reservoir operating, bottom sediment mass can be determined.

Numerous studies of the characteristics of bottom sediments from different water reservoirs (Rzętała, 2003; Gwóźdź, 2007; Kozielska-Sroka, Chęć, 2009; Loska, Cebula, Wiechuła, 2002; Madeyski, Bednarz, 2004) have showed that sediments can be a valuable material in geotechnical engineering, especially when there are no mineral soils near the location of a construction site. Sediments from water reservoirs can be used in different ways:

- as an additive to light soils in order to improve their productive value,
- for ground leveling,
- in land reclamation,
- in geotechnical engineering:
  - for building and modernization of dykes or reservoir slopes,
  - for building road embankments,
  - for forming soil liners in landfills,
  - in hydraulic engineering.

Although sediment characteristics allow to use them for forming cutoff walls in landfills or constructing road embankments, the operating difficulties and concerns related to using sediments cause their rare use. In practice, utilization of bottom sediments is reduced to leveling on the spot and eventually for rebuilding reservoir slopes.

## THE PURPOSE AND RANGE OF THE STUDY

The present research aimed to determine the geotechnical characteristics and heavy metal contents in bottom sediments in the Czorsztyn–Niedzica reservoir backwater and to evaluate their usability for geotechnical engineering, including road engineering purposes, hydraulic engineering, as well as formation of cutoff walls in landfills.

Bottom sediment samples were taken from the backwater at the Dunajec river mouth near Dębno in February 2008 when the water level in the reservoir was lowered because of the works at the earth dam. The sampling depth depended on the variations of granulation in the analyzed profile and reached 0.3 m (surface layer), 0.5–0.7 m, 0.7–0.8 m and 0.9–1.1 m.

The analysis of the geotechnical characteristics was carried out at the Geotechnical Laboratory of the Department of Soil Mechanics and Land Structures at the University of Agriculture in Kraków. The analysis included determination of granulation, specific gravity, compactibility parameters, consistency limits of cohesive sediments, organic matter content, the permeability coefficient and compressibility parameters.

The granulation and the basic physical parameters were determined in a procedure according to the Polish standards. The optimum moisture content and the maximum dry density for cohesive sediments were specified in a Proctor apparatus at the compaction energy of $0.59 J \cdot cm^{-3}$. The compactibility parameters of non-cohesive sediments were defined using the vibration method.

The permeability coefficient for cohesive sediments was determined in eodometers adapted for testing permeability, on samples with a diameter of 7.5 cm and a height of 1.9 cm. The tests were carried out at the compaction index $I_S = 0.95$ and the moisture content close to the optimum one, with the upward water flow and the changeable hydraulic gradient, whereas the permeability coefficient of non-cohesive sediments occurring below 0.7 m was specified in a ITB-ZWk2 apparatus on samples with the diameter of 11.2 cm and the height of 6.2 cm, with the moisture content about 3% and the compactibility corresponding to $I_S = 0.95$. The test was carried out for the water flow in both directions and at a constant hydraulic gradient.

The compressibility tests were carried out in eodometers on samples with a diameter of 7.5 cm and a height of 1.9 cm, at the moisture content close to the optimum one and at the compaction index $I_s = 0.95$. Cohesive sediments taken from the depth of 0.5 m to 0.7 m and non-cohesive ones from the depth of 0.7 m to 0.8 m were selected for the tests. Consecutive primary load steps of 12.5, 25, 50, 100, 200 kPa were kept for 24 hours, and only the last one – 400 kPa– was left until full consolidation. Then the samples were gradually unloaded, and at the next stage they were reloaded. The average values of the compressibility modulus at a load ranging from 0 to 400 kPa were taken for the analysis.

The concentration of heavy metals was determined at the Laboratory of the Department of Ecological Bases of Environmental Engineering at the University of Agriculture in Kraków. The analysis included determination of cadmium (Cd), zinc (Zn), lead (Pb) and cooper (Cu) content by the FAAS method in a UNICAM Solaar M6 spectrometer as well as bottom sediment purity class specification.

## GEOTECHNICAL CHARACTERISTICS OF BOTTOM SEDIMENTS

Sediments taken from the depth down to 0.7 m were classified and silts with the dominant silt fraction content about 83%, sand fraction about 12% and clay fraction somewhat more than 5% were graded (Table 1). Sediments taken from the depth of 0.7 m to 0.8 m were classified as uniformly graded silty sands with the sand fraction content of 83%, silt fraction together with clay fraction about 12%, whereas sediments taken from the depth of 0.9 m to 1.1 m were classified as uniformly graded medium sands with the content of sand fraction 98% and silt and clay fraction 2%.

The natural moisture content of bottom sediments taken from the depth down to 0.7 m amounted from about 55% to 62% and of sediments taken from the depth of 0.7 to 0.8 m and 0.9 to 1.1 m to 21% and 10%, respectively.

The density of solid particles amounted from 2.66 to $2.68 g \cdot cm^{-3}$ in both cohesive and non-cohesive sediments,

Table 1. **Geotechnical parameters of bottom sediments from Czorsztyn–Niedzica reservoir backwater**
1 lentelė. **Dugno nuosėdų iš Čorštyno-Niedzicos rezervuaro geotechniniai parametrai**

| Parameters | Symbol | Unit | Sampling depth, m | | | |
|---|---|---|---|---|---|---|
| | | | 0.0–0.3 | 0.5–0.7 | 0.7–0.8 | 0.9–1.1 |
| Natural moisture content | $w_n$ | % | 55.53 | 62.32 | 21.58 | 9.97 |
| Fraction content: | | | | | | |
| sand 2–0.05 mm | $f_p$ | % | 9.8 | 13.4 | 83.2 | 98.0 |
| silt 0.05–0.002 mm | $f_\pi$ | | 85.0 | 81.2 | 16.6 | 2.0 |
| clay <0.002 mm | $f_i$ | | 5.2 | 5.4 | 0.2 | |
| Uniformity coefficient | U | – | 11.7 | 10.9 | 2.6 | 2.4 |
| Name according to [18] | | | Silt | Silt | Silty sand | Medium sand |
| Specific density | $\rho_s$ | $g \cdot cm^{-3}$ | 2.68 | 2.67 | 2.66 | 2.65 |
| Organic matter content | $I_{om}$ | % | 2.09 | 3.13 | 1.00 | 0.75 |
| Loss on ignition | $I_{\dot{z}}$ | | 6.37 | 7.30 | 2.49 | 1.74 |
| Permeability coefficient | $k_{10}$ | $m \cdot s^{-1}$ | $6.3 \cdot 10^{-9}$ | $3.3 \cdot 10^{-9}$ | $2.2 \cdot 10^{-5}$ | $6.2 \cdot 10^{-5}$ |
| Optimum moisture content | $w_{opt}$ | % | 25.2 | 27.9 | – | – |
| Maximum dry density | $\rho_{ds}$ | $g \cdot cm^{-3}$ | 1.44 | 1.42 | – | – |
| Dry density of solid particles at the most loose packing of grains | $\rho_{dmin}$ | $g \cdot cm^{-3}$ | – | – | 1.21 | 1.24 |
| Dry density of solid particles at the most dense packing of grains | $\rho_{dmax}$ | | – | – | 1.47 | 1.52 |
| Plastic limit | $w_P$ | % | 27.67 | 32.04 | – | – |
| Liquid limit | $w_L$ | | 42.90 | 50.20 | – | – |
| Liquidity index | $I_L$ | – | 1.83 | 1.67 | – | – |
| Primary modulus of compressibility | $M_0$ | MPa | – | 3.24 | 6.89 | – |
| Secondary modulus of compressibility | M | | – | 17.97 | 48.12 | – |

and it was compatible with the values presented in the literature for soils with the analogous granulation as the bottom sediments tested (PN-B-04481:1988).

The compactibility parameters of cohesive sediment silts were as follows: the optimum moisture content varied between about 25% and 28%, whereas the maximum dry density ranged from 1.44 $g \cdot cm^{-3}$ to 1.42 $g \cdot cm^{-3}$. For the non-cohesive sediments classified as silty and medium sand taken from the depth below 0.7 m, the values of the dry density of solid particles at the most loose packing of grains oscillated between 1.21 $g \cdot cm^{-3}$ and 1.24 $g \cdot cm^{-3}$, while the dry density values of solid particles of the most dense packing of grains ranged from 1.47 $g \cdot cm^{-3}$ to 1.52 $g \cdot cm^{-3}$.

Ignition losses for the cohesive soils varied between 6.4% and 7.3%, whereas for the non-cohesive soils taken from the depth of 0.7 m and 0.9 m they amounted to 2.5% and 1.7%, respectively. Organic matter content obtained by the oxidation method for cohesive sediments was on average 2.6%, and for non-cohesive sediments it did not exceed 1.0%. According to the standard PN-B-04481:1988, the value of the loss on ignition should be treated as approximate while classifying soils. The oxidation method is a proper one, and on its basis it was found that sediments taken from the depth down to 0.7 m were humus soils. Sediments below 0.7 m were classified as mineral soils.

The permeability coefficient of cohesive sediments taken from the depth of 0.0–0.3 m and 0.5–0.7 m averaged to $4.5 \cdot 10^{-9}$ $m \cdot s^{-1}$, whereas for non-cohesive sediments taken from the depth of 0.7–0.8 m it amounted to $2.15 \cdot 10^{-5}$ $m \cdot s^{-1}$ and for sediments from the depth of 0.9 m to $6.17 \cdot 10^{-5}$ $m \cdot s^{-1}$.

The values of primary and secondary moduli of compressibility for cohesive sediments taken from the depth 0.5–0.7 m, classified as silt, were more than half as low than the values for non-cohesive sediments taken from the depth 0.7–0.8 m, classified as silty sand. However, the values of secondary moduli of compressibility for cohesive sediments were about five and a half times and for non-cohesive sediments seven times higher than the primary moduli of compressibility.

## CONTENT OF HEAVY METALS

The evaluation of usability of bottom sediments for geotechnical engineering purposes requires also determination of heavy metal pollution. There is a conviction that bottom sediments are useless because of a high heavy metal content. However, numerous authors (Gwóźdź, 2007; Loska, Cebula, Wiechuła, 2002; Madeyski, Bednarz, 2004; Juracek, 2003) indicate that in many cases the concentration of these metals is below the level that allows sediments to be used for various engineering purposes.

The pollution level of bottom sediments from the Czorsztyn–Niedzica reservoir backwater was defined on the basis of cadmium, lead, zinc and cooper content. Analysis showed that in non-cohesive sediments zinc content was two or three times lower, lead and copper content three times and cadmium content more than three times lower than in cohesive sediments (Table 2).

On the grounds of heavy metal content, sediments can be classified as belonging to a certain purity class based on geochemical criteria (Bojakowska, Sokołowska, 1998). This classification (Table 3) does not determine the usability of bottom sediments in geotechnical engineering; it is only the evaluation of sediment purity. In case of cadmium (Cd), lead (Pb) and zinc (Zn), sediments taken from the depth down to 0.7 m were classified as of class I purity, whereas in sediments from the depth below 0.7 m the content of these metals did not exceed the geochemical background value. In case of copper, sediments taken from the depth down to 0.7 m were classified as of class II and below that depth as of class I purity.

However, criteria of allowable heavy metal content that can occur in soils, also those used in earth works as well as bottom sediments from water reservoirs, are included in the Regulation of the Minister of Environment concerning the quality standards for soils and grounds (Dz. U. 2002, nr 165, poz. 1359). According to this law, soil is classified as polluted when the concentration of at least one substance exceeds the permissible level.

Upon comparing the concentration values of mentioned metals with the permissible values for group A soils from the Regulation of the Minister of Environment, it was stated that no threshold values were exceeded (Table 2). Only in case of cohesive sediments, zinc and copper content insignificantly approached the threshold values. Based on these facts and in accordance with the mentioned regulation, the examined bottom sediments can be used for geotechnical engineering purposes.

A comparison of heavy metal content in bottom sediments from the Czorsztyn–Niedzica reservoir and from reservoirs located in the U. S. A. (Juracek, 2003; Lee, Faure, Bigham, Williams, 2008; Juracek, 2006b) has shown that the cadmium concentrations are on the comparable level, whereas lead, zinc and copper concentrations are significantly lower in the Czorsztyn Reservoir than in the American reservoirs (Table 4). In case of Lake Empire and Lake Ocoee, the increased concentration of lead, zinc and copper is a result of the mining activity. In drainage areas of these reservoirs copper or zinc mines are located; also, the vehicular traffic in the basins is increased.

## ANALYSIS OF USABILITY OF BOTTOM SEDIMENTS

The usability of bottom sediments for geotechnical engineering purposes was assessed according to the requirements of the PN-B-06050:1999 and PN-S-02205:1998

Table 2. **Content of heavy metals in bottom sediments from Czorsztyn–Niedzica reservoir backwater and their classification**
2 lentelė. **Sunkiųjų metalų kiekis dugno nuosėdose iš Čorštyno-Niedzicos rezervuaro**

| Sampling depth | Cadmium (Cd) | | | Lead (Pb) | | | Zinc (Zn) | | | Cooper (Cu) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Content | Threshold value[1)] | Purity class[2)] | Content | Threshold value | Purity class | Content | Threshold value | Purity class | Content | Threshold value | Purity class |
| m | mg · kg$^{-1}$ of dry matter | | | mg · kg$^{-1}$ of dry matter | | | mg · kg$^{-1}$ of dry matter | | | mg · kg$^{-1}$ of dry matter | | |
| 0.0–0.3 | 0.46 | 1.0 | B | 16.1 | 50 | I | 84.7 | 100 | I | 25.3 | 30 | II |
| 0.5–0.7 | 0.54 | | I | 19.3 | | I | 99.4 | | I | 29.4 | | II |
| 0.7–0.8 | 0.18 | | B | 7.2 | | B | 45.9 | | B | 11.7 | | I |
| 0.9–1.1 | 0.12 | | B | 5.2 | | B | 32.0 | | B | 7.2 | | I |

[1)] Based on the Minister of Environment Regulation (Dz. U. 2002, No. 165, pos. 1359);
[2)] Based on (Bojakowska, Sokołowska 1998)
B – background.

Table 3. **Classification of bottom sediments based on geochemical criteria for chosen heavy metals (Bojakowska, Sokołowska, 1998)**
3 lentelė. **Dugno nuosėdų klasifikacija remiantis sunkiųjų metalų geocheminiais kriterijais**

| Heavy metal | Purity class | | | |
|---|---|---|---|---|
| | Geochemical background | I | II | III |
| | Allowable content, mg/kg of dry matter | | | |
| Cadmium (Cd) | <0.5 | <1 | <5 | <20 |
| Lead (Pb) | <10 | <50 | <200 | <500 |
| Zinc (Zn) | <48 | <200 | <1000 | <2000 |
| Copper (Cu) | <6 | <20 | <100 | <200 |

Table 4. **Heavy metal content in bottom sediments of water reservoirs**
4 lentelė. **Sunkiųjų metalų kiekis vandens rezervuarų dugno nuosėdose**

| Constituent | Czorsztyn–Niedzica Reservoir, Poland | Lake Empire , Kansas, USA [12] | Blackberry Hay Farm Lake, Missouri, USA [12] | Lake Ocoee No. 3 Tennessee, USA [11] | Lake Perry, Kansas, USA [9] |
|---|---|---|---|---|---|
| | mg · kg$^{-1}$ | | | | |
| Cadmium (Cd) | 0.12–0.46 | 29 | 0.4 | 0.35 | 0.5 |
| Lead (Pb) | 5.2–19.3 | 270 | 33 | 41.7 | 28 |
| Zinc (Zn) | 32.0–99.4 | 4 900 | 92 | 170 | 120 |
| Copper (Cu) | 7.2–29.4 | – | – | 270 | 33 |

standards. Standard recommendations refer mainly to constructing embankments, especially road ones; therefore, in the analysis of usability of sediments for hydraulic engineering purposes and for forming mineral cutoff walls in landfills, instructions from professional literature were also used.

## EVALUATION OF USABILITY FOR CONSTRUCTING ROAD EMBANKMENTS

Bottom sediments classified as silts and silty sand can be preliminarily allowed to be used in the top and bottom layers of road embankments with reservations (PN-S-02205:1998). These reservations refer to building sediments in dry places or places that are protected from underground and surface water as well as improving sediments with a hydraulic binding agent in freezing zones. Only in case of medium sands, the PN-S-02205:1998 standard classifies them as suitable. Nevertheless, according to the mentioned standard, while choosing these soils for constructing embankments, additional requirements should be taken into account.

The research results (Table 5) allow stating that the examined bottom sediments are characterized by the geotechnical parameters that do not fulfil the additional criteria of the relevant standards. The cohesive sediments are soils subject to frost-heave with organic matter content over 2% and the maximum dry density below the required 1.6 t · m$^{-3}$. Also, the upper liquid limit was exceeded in case of using sediments for top layers of embankments. As to non-cohesive sediments, silty sand was classified as questionable as regards the frost-heave and also the obtained value of the uniformity coefficient classifies these sediments as the soil conditionally allowed for use, after verification of the possibility of getting the required compactibility on an experimental plot. Medium sand has the best parameters, although, because of the low value of the uniformity coefficient, it is only conditionally allowed for use.

To sum up, it can be stated that the examined sediments can be used for constructing embankments under condition that part of their geotechnical parameters are improved, for example, through stabilization with hydraulic binding agents.

## EVALUATION OF THE USABILITY OF SEDIMENTS FOR HYDRAULIC ENGINEERING PURPOSES

In case of using sediments for hydraulic engineering purposes, the required graining criterion was not reached because of the too low sand-gravel fraction content (Sobczak, 1975). It is recommended to use very well graded soils with U > 60, whereas the value obtained for the examined cohesive sediments was U < 12 (Table 6) and for non-cohesive ones around 2.5. Also, clay fraction content was much lower than 20%. Additionally, organic matter content was too high – over 2%. Still it should be emphasized that the minimum value of the permeability coefficient at the compaction corresponding to $I_S = 0.95$ was reached for both non-cohesive (the use for construction embankment bodies) and cohesive sediments (the use for sealings). Analysis of test results regarding the use of alluvial soils for the construction of embankments (Gwóźdź, 2007) has shown that these sediments can be used when forming low hydraulic embankments.

## EVALUATION OF THE USABILITY OF BOTTOM SEDIMENTS FOR FORMING LANDFILL LINERS

Landfill liners are built most often of cohesive soils characterized by the geotechnical parameters limiting the level of leachate filtration. Therefore, to evaluate the usability for constructing such layers, cohesive sediments taken from two levels from the depth down to 0.7 m were selected. The Regulation of the Minister of Environment about construction of waste disposal sites contains basic instructions for using soils (Dz.U. 2003, nr 61, poz. 549); according to this law, the permeability criterion for landfill liners is that the permeability coefficient $k_{10} \leq 10^{-9}$ m/s. Additional recommendations and criteria, depending on landfill type and structure, are available in the related literature. The criteria of permeability, granulation and plasticity are acknowledged as the basic ones that influence the quality of landfill liners (Wysokiński, 2007).

The obtained value of the permeability coefficient for the examined cohesive sediments indicates that the criterion of permeability is fulfilled. With the compactibility corresponding to $I_S = 0.95$, this coefficient equals on average

Table 5. **Evaluation of the usability of bottom sediments for building road embankments according to standards (Bojakowska, Sokołowska, 1998; Lee, Faure, Bigham, Williams, 2008)**

5 lentelė. **Dugno nuosėdų panaudojimo kelių sankasoms vertinimas (Bojakowska, Sokołowska, 1998; Lee, Faure, Bigham, Williams, 2008)**

| Evaluation criteria | | Unit | Standard requirements | Determined values for each sampling depth | | |
|---|---|---|---|---|---|---|
| | | | | 0.0–0.7 m | 0.7–0.8 m | 0.9–1.1 m |
| Name according to [18] | | | | Silt | Silty sand | Medium sand |
| Maximum grain size | | mm | 200 | Absence of grains over 200 mm | | |
| Uniformity coefficient, U | | – | ≥3 | 10.9–11.7 | 2.6 | 2,4 |
| Organic matter content, $I_{om}$ | | % | <2 | 2.09–3.13 | 1.00 | 0,75 |
| Maximum dry density, $\rho_{ds}$ | | $g \cdot cm^{-3}$ | ≥1.6 | 1.42–1.44 | Not determined | |
| Liquid limit, $w_L$ | Top layers of embankments | % | <35 | 42.9–50.2 | Not determined | |
| | Bottom layers of embankments | | <65 | | | |
| Particle content: | | % | Depending on soil group | | | |
| ≤0.075 mm | | | | 91 | 23 | 3,5 |
| ≤0.02 mm | | | | 51 | 2 | 1 |
| Heave group | | – | | Subjected to frost-heave | Questionable | Not subjected to frost-heave |

Table 6. **Evaluation of usability of bottom sediments for hydraulic engineering purposes (Sobczak, 1975)**

6 lentelė. **Dugno nuosėdų panaudojimo hidraulinės inžinerijos tikslams vertinimas**

| Evaluation criteria for the place of building in the embankment | | Unit | Recommendations | Determined values for each sampling depth | | |
|---|---|---|---|---|---|---|
| | | | | 0.0–0.7 m | 0.7–0.8 m | 0.9–1.1 m |
| Name according to [18] | | | | Silt | Silty sand | Medium sand |
| Organic matter content, $I_{om}$ | | % | <3 | 2.1–3.1 | 1.0 | 0.75 |
| Uniformity coefficient, U | Body | – | >60 | 10.9–11.7 | 2.6 | 2.4 |
| Clay fraction content, $f_i$ | Seal | % | >20 | 5.2–5.4 | 0.2 | 0 |
| Permeability coefficient, $k_{10}$ | Body | m/s | $<10^{-4}$ | $6.3 \cdot 10^{-9}$–$3.3 \cdot 10^{-9}$ | $2.2 \cdot 10^{-5}$ | $6.2 \cdot 10^{-5}$ |
| | Seal | | $<10^{-6}$ | | | |

Table 7. **Evaluation of usability of bottom sediments for forming landfill liners**

7 lentelė. **Dugno nuosėdų panaudojimo šiukšlynų sankasoms vertinimas**

| Evaluation criteria | Unit | Recommendations | Determined values of cohesive sediments |
|---|---|---|---|
| Name according to [18] | | | Silt |
| Permeability coefficient, $k_{10}$ | $m \cdot s^{-1}$ | $\leq 1 \cdot 10^{-9}$ | $6.32 \cdot 10^{-9}$–$3.27 \cdot 10^{-9}$ |
| Clay fraction content, $f_i$ | % | ≥20 | 5.2–5.4 |
| Organic matter content, $I_{om}$ | | ≤2–5 | 2.09–7 3.13 |
| Plasticity index, $I_p$ | | 7–65 | 15.13–18.26 |

to $4.8 \cdot 10^{-9}$ m $\cdot$ $s^{-1}$ (Table 7). The criterion of granulation specifies that soils with the clay fraction content over 20% have the best filter characteristics for forming landfill liners, whereas the standard PN-B-06050:1999 considering workability recommends using soils with the clay fraction content below 30%. The granulation analysis showed cohesive sediments to contain slightly more than 5% of clay fraction; thus the criterion of granulation is not fulfilled. However, taking into consideration the low value of the permeability coefficient, it can be assumed that by adding soils with a large clay fraction content to the bottom sediments, a useful material for forming insulation layers can be obtained.

The criterion of plasticity indicates the technical possibilities of forming mineral cutoff walls. It makes the use of soils dependent on the value of the plasticity index. Tests showed that the soils with the plasticity index from 10 to 30 which, in case of the examined sediments, is fulfilled, have the best forming features and also the best permeability parameters.

## CONCLUSIONS

The results of geotechnical research and the content of heavy metals in bottom sediments from the Czorsztyn–Niedzica reservoir backwater were as follows:

1. The bottom sediments taken from the depth down to 0.7 m were classified as cohesive humus silts and the soils below that depth as non-cohesive (silty and medium sands).

2. The analysis of cadmium (Cd), zinc (Zn) and lead (Pb) content showed a low concentration of these metals in the sediments on the geotechnical background level. Only copper (Cu) content showed an increased concentration, but it did not exceed the class II of sediment purity.

3. The tested sediments did not fulfil most of the required criteria and therefore rather cannot be used for geotechnical engineering purposes. However, in case of sediment extraction, the possibility of improving granulation or stabilization with a hydraulic binding agent and reexamination of foregoing criteria should be considered.

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**Andrzej Gruchot, Karolina Sudyka**

### ČORŠTYNO-NIEDZICOS REZERVUARO DUGNO NUOSĖDŲ PANAUDOJIMO GEOTECHNINĖS INŽINERIJOS TIKSLAMS VERTINIMAS

*S a n t r a u k a*

Ištirtos Čorštyno-Niedzicos rezervuaro dugno nuosėdų geotechninės savybės ir sunkiųjų metalų koncentracija. Bandiniai, paimti iki 0,7 m gylio, klasifikuojami kaip kompaktiškas humusingas aleuritas, o giliau esančios nuosėdos priskiriamos nekompaktiškam aleuritui ir vidutingrūdžiam smiltainiui. Kadmio, cinko ir švino nuosėdose yra nedaug (geotechninio fono lygis), tik vario kiekis yra didesnis, tačiau jis yra II nuosėdų švarumo lygio. Vis dėlto bendros nuosėdų charakteristikos netenkina geotechninės inžinerijos keliamų reikalavimų. Vykdant valymo darbus rezervuare nuosėdų parametrus galima pagerinti granuliuojant arba stabilizuojant hidrauliniais rišikliais.


**Raktažodžiai: dugno** nuosėdos, rezervuarai, sunkiųjų metalų kiekiai, geotechninės charakteristikos