Geotechnical characteristics of unburnt colliery spoils after coal-recovery

Tymoteusz Zydroń[1], *Andrzej* Gruchot[1,*], and *Eugeniusz* Zawisza[1]

[1]University of Agriculture in Kraków, Faculty of Environmental Engineering and Geodesy, Department of Hydraulic Engineering and Geotechnics, 24/28 Adama Mickiewicza Avenue, 30-059 Kraków, Poland

Abstract. The aim of the study was to determine the geotechnical characteristics of the unburnt colliery spoils after coal-recovery from the dumping site of one of the mines of the Upper Silesian Coal Basin in Poland. Due to grain-size distribution of tested spoils their geotechnical properties were determined using medium-sized apparatuses. In order to verify the suitability of the studied spoils for the construction of hydraulic embankments, the seepage and stability calculations were conducted for models of hydraulic embankments including the effect of flood wave passage on stress conditions within the construction and their slope stability. The test results revealed, that the studied colliery spoils are characterized by favourable values of geotechnical parameters and they fulfil the requirements for soil materials used in the analysed type of constructions. The spoils are characterized by good compactibility, relatively low water permeability and average susceptibility to mechanical disintegration, which in the case of using this material for the construction of hydraulic embankments and using proper compaction technology, should reduce their susceptibility to weathering. The results of seepage and slope stability calculations for hydraulic embankments built of the studied spoils confirmed their suitability for that type of constructions, retaining the proper inclination of slopes, whereas the variant of embankment without sealing is safer from the stability viewpoint.

1 Introduction

Climatic changes observed in recent years cause that proper water management has become increasingly important. In Poland, only in 1997-2010 there were several intense rainfall periods followed by floods. One of the methods to reduce the negative effects of floods is the construction of hydrotechnical objects of small and large retention (dikes, reservoirs, flood polders). Construction of such objects requires however huge amount of earth material, the resources of which are limited. Therefore, for many years anthropogenic soils, including colliery spoils of hard coal mining, have been an alternative for mineral soils. These materials are characterized by a relatively high variability of geotechnical characteristics, which causes that each time they require determination of parameters characterizing their physical and mechanical properties in terms of their use for earth constructions [1-5]. Most of the industrial wastes linger in landfills that take sometimes considerable areas of land creating degraded zones. The elimination of dumping grounds through the use of waste for the engineering purposes has a significant influence on shaping and protection of the environment [6, 7].

2 Research aim and methods

The subject of research were unburnt colliery spoils from the dumping site of one of the mines of the Upper Silesian Coal Basin in Poland. The study material included crushed colliery spoils after coal-recovery with grain size of 0–100 mm.

The aim of the study was to determine the geotechnical characteristics of the mentioned colliery spoils in terms of their suitability for the construction of hydraulic embankments. Physical and mechanical properties were determined by standard methods used in geotechnical engineering for mineral soils, whereas the dimensions of experimental equipment were adapted to the grain size of the studied material.

The grain size composition was determined by the combined method, i.e. sieving for fractions larger than 0.063 mm and aerometry for smaller fractions. The analysis was conducted for fresh material and for material subjected to compaction in the Proctor apparatus.

Density of solid particles was determined by using the measuring flask for particles smaller than 0.063 mm and for the sample separated from the material of full grain size and crushed to a fraction smaller than 0.25 mm. The content of organic matter was determined by oxidation, while loss on ignition was determined based on the mass loss of samples at the temperature of 750°C.

*Corresponding author: rmgrucho@cyf-kr.edu.pl

Determination of compactibility parameters for material with particle size smaller than 63 mm was carried out in a medium-size Proctor apparatus with cylinder volume of 9.8 dm^3 at standard (0.59 $J \cdot cm^{-3}$) compaction energy. For comparison purposes, the examination was also conducted in a standard Proctor apparatus with cylinder volume of 2.2 dm^3, for material with grain size smaller than 31.5 mm at standard (0.59 $J \cdot cm^{-3}$) and modified (2.65 $J \cdot cm^{-3}$) compaction energy.

Permeability coefficient was determined for material with grain size smaller than 63 mm, in a medium-size permeameter with diameter and height of sample equal to 0,36 m. The samples were formed in the apparatus cylinder at optimum moisture content until obtaining the compaction index of I_S = 0.90 and 0.97. The analyzes were conducted at a sample load equal to 10 kPa using two directions of water flow – from bottom to top and from top to bottom. The measurements were carried out after percolation of water through the sample and stabilization of flow, at steady hydraulic gradient. The values of permeability coefficient obtained for both water flow directions were averaged and converted to the referenced temperature of 10°C. The apparatus applied meets the conditions for the determination of water permeability of coarse-grained soils:

- inner diameter of the apparatus cylinder was greater than five times the maximum diameter of soil grain,
- the length of filtration path equals to the inner diameter of the apparatus cylinder.

Shear strength was determined for the material with grain size smaller than 63 mm, in a medium-size apparatus of direct shear in a box with dimensions of 0,3×0,3×0,2 m with intermediate frames forming shear zone of 30 mm height. The use of intermediate frames allows zonal shearing, limiting the impact of grain overlapping and wedging on the cohesion value (so-called apparent cohesion). The analyzes were carried out on samples formed directly in the apparatus box at the moisture content corresponding to the optimum required for obtaining the degree of compaction of I_S = 0.95.

The frost resistance was tested for the material with a grain size of 4-63 mm, for samples divided into fractions 4–8, 8–16, 16–31.5 and 31.5–63 mm. The test samples were rinsed with water in order to remove fine particles adhering to the grains, and then they were dried to constant weight at a temperature of 105–110°C. Such prepared samples were placed in cuvettes and soaked in water at a temperature of 20°C for 24 hours. Then the samples were subjected to freeze-thawing cycles by using the following procedure for each cycle:

- decreasing temperature from 20°C to 0°C during 2 hours and held for 3 hours,
- decreasing sample temperature from 0°C to -18°C during 3 hours and held for 5 hours,
- after freezing was finished, the sample was thawed by immersion in water with a temperature of 20°C for 11 hours.

After 10 cycles of freeze-thawing, the samples were rinsed with water to remove the damaged grains. Rinsing was conducted on a sieve of mesh size equal to half the diameter of the smallest grains of the analyzed fraction, i.e.: 2, 4, 8, 16 and 32 mm. Residual on the sieves was dried to constant weight and weighed. Frost resistance of the material with a grain size of 4–63 mm was calculated as a weighted average of the values obtained for individual fractions.

In order to verify the suitability of the studied waste for the construction of hydraulic embankments, the seepage and stability calculations were conducted for models of hydraulic embankments with regard to the effect of flood wave passage on stress conditions within the construction and their slope stability. The calculations were carried out in the GeoStudio package.

3 Results and discussion

3.1 Geotechnical characteristics and evaluation of colliery spoils suitability for the construction of hydraulic embankments

In terms of geotechnical properties, colliery spoils were classified as gravel with a dominant gravel fraction, reaching 72% in the full-grained material and more than 80% in the material with grain size smaller than 63 and 31.5 mm. The sand fraction ranged from 9 to more than 12%, silt – from more than 3 to almost 5%, while clay fraction content was below 3%. In terms of uniformity coefficient (C_U = 23.33) the material was defined as multi-fractional [8], which allows to predict its good compactibility during incorporation into the embankment. However, it should be taken into consideration that during compaction the grain size composition of the material may be subjected to changes due to the impact of mechanical factors. A good source of information about the resistance of the studied spoils to the processes of mechanical and physical disintegration were the examinations of the grain size after their compaction by standard and modified energy in the Proctor apparatus (Table 1, Fig. 1).

The results of analyzes showed that the compaction of the material causes its fragmentation, expressed by the loss in the gravel fraction in favour of finer fractions, mainly sand. A positive effect of spoils fragmentation is the increase in their uniformity coefficient, whose high values are characteristic for soils of good compactibility. Overall, the size of coarse fraction loss in favour of fine fractions is not large in relation to the changes in grain size for the unburnt colliery spoils from the Upper Silesian Coal Basin [4], or from other regions [9].

Density of solid particles was 2.60 $t \cdot m^{-3}$ and was high as compared to the values reported in Polish and foreign literature [4] for colliery spoils (Table 1). The organic matter content was small (0.22%) and met the requirements for materials used for the construction of civil engineering embankments. On the other hand, loss on ignition was 11% and was much smaller than the one for the typical unburnt colliery spoils from the Upper

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Silesian Coal Basin [4], which indicates low susceptibility of this material to self-ignition.

Table 1. Geotechnical properties of colliery spoils

Parameter		Value
Density of solid particles [$t \cdot m^{-3}$] for:	d < 0.063 mm	2.56
	d < 100 mm	2.60
Natural moisture [%]		5.73
Organic matter content [%]		0.22
Weight loss on ignition [%]		11.29
Maximum dry density [$t \cdot m^{-3}$] for:	d < 63 mm at $E_z = 0.59\ J \cdot cm^{-3}$	2.12
	d < 31 mm at $E_z = 0.59\ J \cdot cm^{-3}$	2.05
	d < 31 mm at $E_z = 2.65\ J \cdot cm^{-3}$	2.16
Optimum moisture content [%] for:	d < 63 mm at $E_z = 0.59\ J \cdot cm^{-3}$	7.6
	d < 31 mm at $E_z = 0.59\ J \cdot cm^{-3}$	7.7
	d < 31 mm at $E_z = 2.65\ J \cdot cm^{-3}$	6.3
Permeability coefficient [$m \cdot s^{-1}$] at the compaction ratio:	$I_S = 0.90$	$7.4 \cdot 10^{-5}$
	$I_S = 0.97$	$1.4 \cdot 10^{-6}$
Frost resistance [%]		17.4
Angle of internal friction [°] at $I_S = 0.95$		36.0
Cohesion [kPa] at $I_S = 0.95$		26.6
where: E_z – compaction energy; I_S –compaction index		

The studied material was characterized by high values of maximum dry density of the matrix at standard compaction energy (2.12 $t \cdot m^{-3}$) which was significantly greater than the values required for the earthworks purposes (1.60 $t \cdot m^{-3}$) [15], as well as than the values of this parameter reported in the literature for unburnt colliery spoils [7, 16, 17]. Tests, carried out in the standard Proctor apparatus on material with granulation smaller than 31.5 mm showed that with standard compaction energy the maximum dry density was 2.05 $t \cdot m^{-3}$, which is less than the value obtained from the medium-size apparatus. On the other hand, the optimum moisture content (7.7%) was practically the same as the one obtained from the medium-size apparatus (7.6%). The test with modified energy allowed to obtain an increase in the maximum dry density up to the value of 2.16 $t \cdot m^{-3}$ and decrease in the optimum moisture content (6.3%) compared to the parameters obtained with standard energy, which is characteristic test carried out at different compaction energies [10]. High compactibility of the studied colliery spoils should be treated as their positive feature. According to the studies [4, 11], this feature decreases the intensity of physical weathering (decomposition of spoils influenced by the processes of recurring soaking and drying).

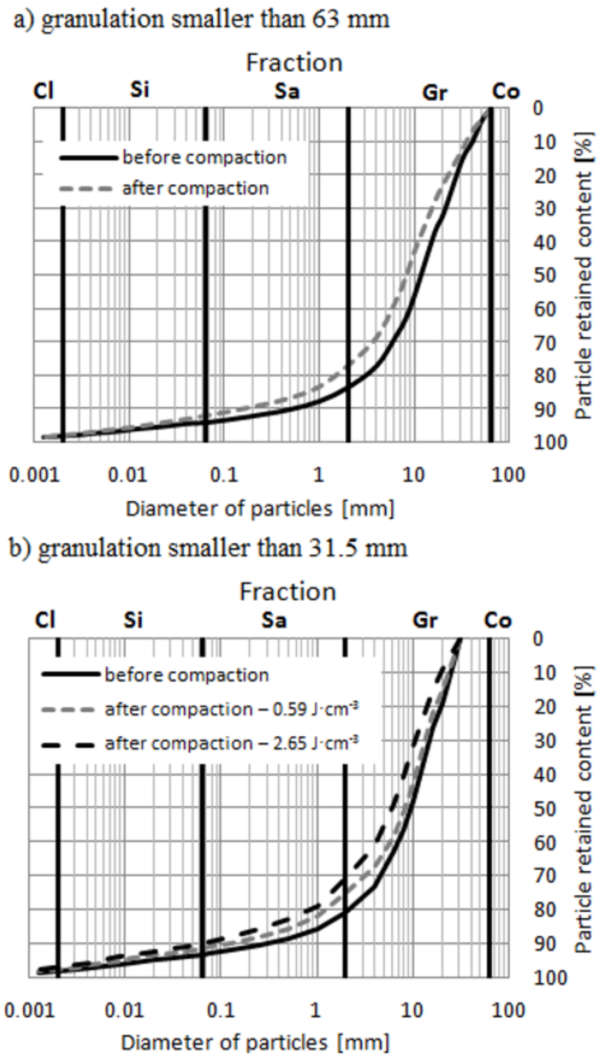


Fig. 1. Disintegration of granulation of colliery spoils after compaction.

Shear strength tests showed that the spoils were characterized by high values of angle of internal friction (36°) and cohesion (27 kPa), which in this type of material is caused by grain wedging. Therefore, this parameter was omitted in the calculations of stability.

Permeability coefficient of the spoils was $7.4 \cdot 10^{-5}\ m \cdot s^{-1}$ at $I_S = 0.90$ and $1.5 \cdot 10^{-6}\ m \cdot s^{-1}$ at $I_S = 0.97$ which indicates significant impact of compaction on water permeability of the studied material. With low compaction the material was moderately permeable, while with high compaction it was less permeable. It should be noted that the obtained values of permeability coefficient of the studied material with high compaction are smaller than for other colliery spoils subjected to coal recovery, originating from the Upper Silesian Coal Basin [12].

Frost resistance test showed that the intensity of the cyclic process of freezing and thawing of colliery spoils varied for individual fractions. Frost resistance values ranged between 13 and 15% for fine fractions (4–8 and 8–16 mm) and between 20 and 23% for coarser fractions (16–31.5 and 31.5–63 mm). The results indicate that spoils disintegration due to the impact of freezing temperatures and water occurs to a greater extent in coarser fractions than in the smaller ones, which was similar to mechanical spoils disintegration which occurs during compaction in the Proctor apparatus. The mean frost resistance for the entire grain size range of the examined waste (4–63 mm) was more than 17%. This value indicates that susceptibility to frost disintegration was average, but clearly higher than in the case of colliery spoils with predominant content of sandstone crumbs originating from preparatory works and smaller than in the spoils subjected to coal recovery from the area of the Upper Silesian Coal Basin. Given the above, it seems reasonable to use the studied spoils in engineering constructions with the cover layer of mineral soils with thickness of at least 1.0 m. This layer will protect the material from exposure to freezing temperatures.

3.2 Calculations of seepage and stability of embankments constructed from colliery spoils

To determine the applicability of the studied colliery spoils for engineering purposes the stability calculations were carried out for the model of the hydraulic embankment slope constructed from the tested material. In order to reduce the possibility of self-ignition, but also to reduce the intensity of physical weathering of the material, the protective layer of sandy gravel with similar filtration properties to colliery spoils was used. The embankment height was adopted as equal to 6.0 m, while the slope inclination of both slopes – as identical and equal to 1:1.75, 1:2, 1:2.25 and 1:2.5. The calculations were performed for four different variants reflecting various geotechnical conditions of the subsoil and sealing of the embankment and its subsoil:

1. permeable subsoil made of medium sands with permeability coefficient of $1 \cdot 10^{-4}$ m·s^{-1},
2. low permeable subsoil made of silty clay with permeability coefficient of $5 \cdot 10^{-8}$ m·s^{-1},
3. permeable subsoil made of medium sand with permeability coefficient of $1 \cdot 10^{-4}$ m·s^{-1}, additionally the vertical barrier made of silty clay with permeability coefficient of $5 \cdot 10^{-8}$ m·s^{-1} was adopted as sealing of the embankment and subsoil,
4. low permeable subsoil made of silty clay with permeability coefficient of $5 \cdot 10^{-8}$ m·s^{-1}, with vertical sealing of the embankment made of soil like in subsoil.

For each variant it was assumed that the embankment is subjected to a 23-day high water level rising and falling (Fig. 2); maximum water level is equal to a height of 1 m from the embankment crest.

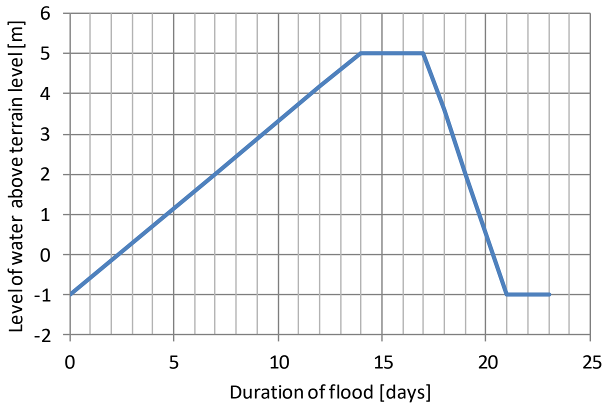


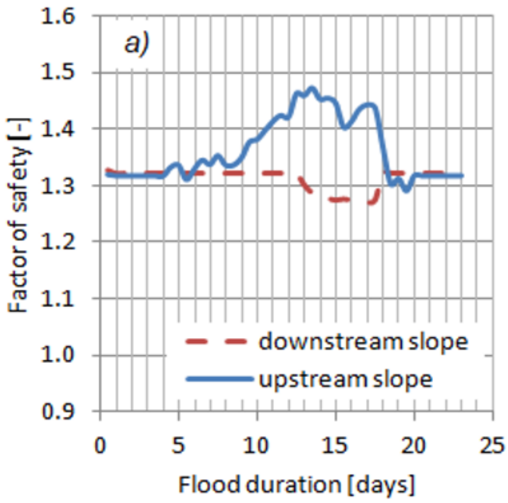
Fig. 2. Flood wave hydrograph

The calculations of seepage through the embankment and its subsoil as well as its stability were performed in the Geostudio programme using SEEP/W and SLOPE/W modules provided by the Department of Geomorphology of the UMCS in Lublin. The retention properties of unsaturated medium for each of the analyzed soils were adopted based on data from the database of soils, which is the part of the application. On the other hand, the hydraulic properties of unsaturated medium were determined using the Mualem equation, presented in the paper by van Genuchten [13]. In the case of colliery spoils the retention characteristics were adopted analogically to the gravel soils.

Table 2 summarizes the values of safety factors for four calculation variants. Figure 3 shows examples of the results of changes in the factor of safety for both slopes of the embankment during the flood wave passage, while Figure 4 illustrates the examples of results of stability calculations in the most adverse periods of floods. The obtained results of calculations indicate a significant impact of geological-engineering conditions and geometric parameters of the embankment on its stability. It can be noticed that more favourable stability conditions occur when the construction subsoil is of permeable soil with permeability greater than the analyzed colliery spoils. In such case the subsoil plays the role of a drainage layer, which results in lowering of the piezometric water line. Much less favourable stability conditions occur when the subsoil is less permeable. Such geological conditions promote the accumulation of flood water within the embankment and the upstream slope is particularly vulnerable to failure. Initially, while rising the flood water level in the inter-embankment zone, the stability of upstream slope increases, which is caused by water pressure on the slope. However, while falling the flood water level, its part remains accumulated in the embankment, which contributes to the stimulation of seepage forces, resulting in a sudden decrease in the value of the factor of safety. This relationship was also observed when the subsoil is made of permeable deposits, but in this case the minimum values of the factor of safety for the upstream slope was, however, slightly higher than in the case of the downstream slope. It should be noted, that safe values of the factor of safety, corresponding to the hydraulic embankments (FS = 1.5) [14] are guaranteed by inclinations of at least 1:2.25, while in the case of unfavourable subsoil conditions (impermeable soil) one may expect safe values of the factor of safety at the inclination of 1:2.5 or higher. It should be also considered that larger water level will result in a greater risk of failure.

Table 2. Summary of stability calculation results

Calculation variant	Slope type	Factor of safety FS [-] at inclination of slopes			
		1:1.75	1:2	1:2.25	1:2.5
Permeable subsoil	Down-stream	1.271	1.379	1.533	1.692
	Up-stream	1.290	1.417	1.553	1.539
Low permeable subsoil	Down-stream	1.332	1.378	1.476	1.561
	Up-stream	1.126	1.222	1.295	1.383
Permeable subsoil, embankment and subsoil sealed with a vertical barrier	Down-stream	1.311	1.407	1.545	1.720
	Up-stream	1.288	1.413	1.590	1.741
Low permeable subsoil and embankment sealed with a vertical barrier	Down-stream	1.289	1.378	1.473	1.569
	Up-stream	1.113	1.216	1.293	1.380



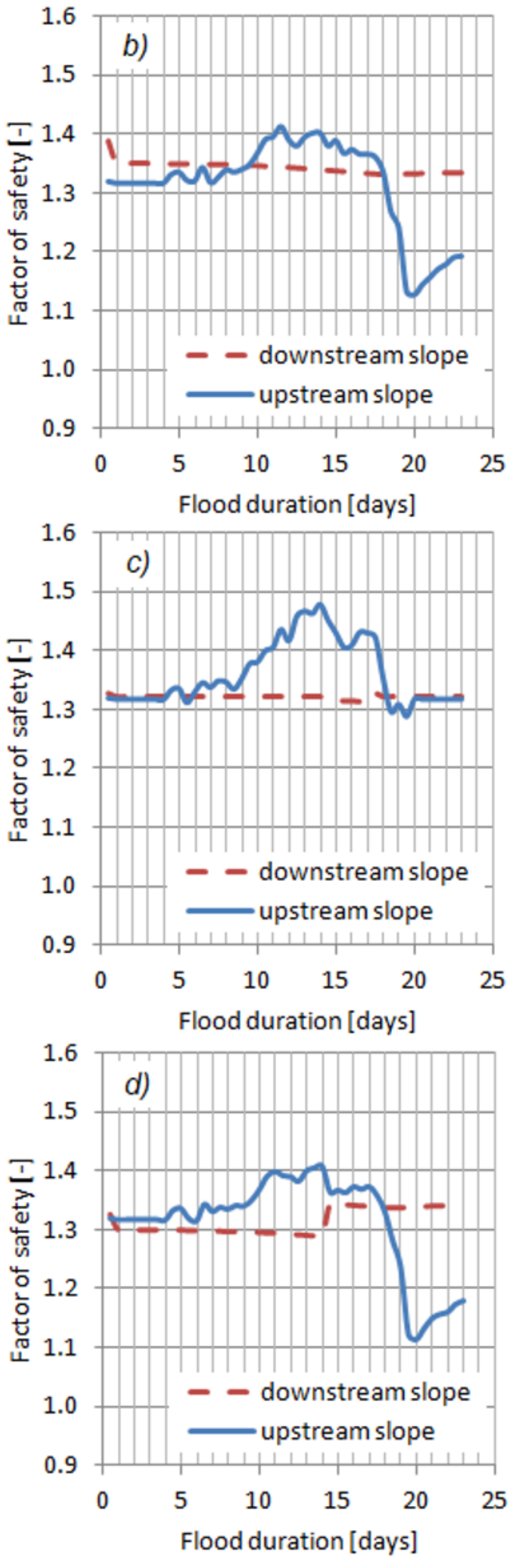


Fig. 3. Results of stability calculations for the embankment with slope inclination of 1:1.75 for permeable subsoil (a), low permeable soil (b), permeable subsoil, embankment and subsoil sealed with a vertical barrier (c), low permeable subsoil and embankment sealed with a vertical barrier (d).

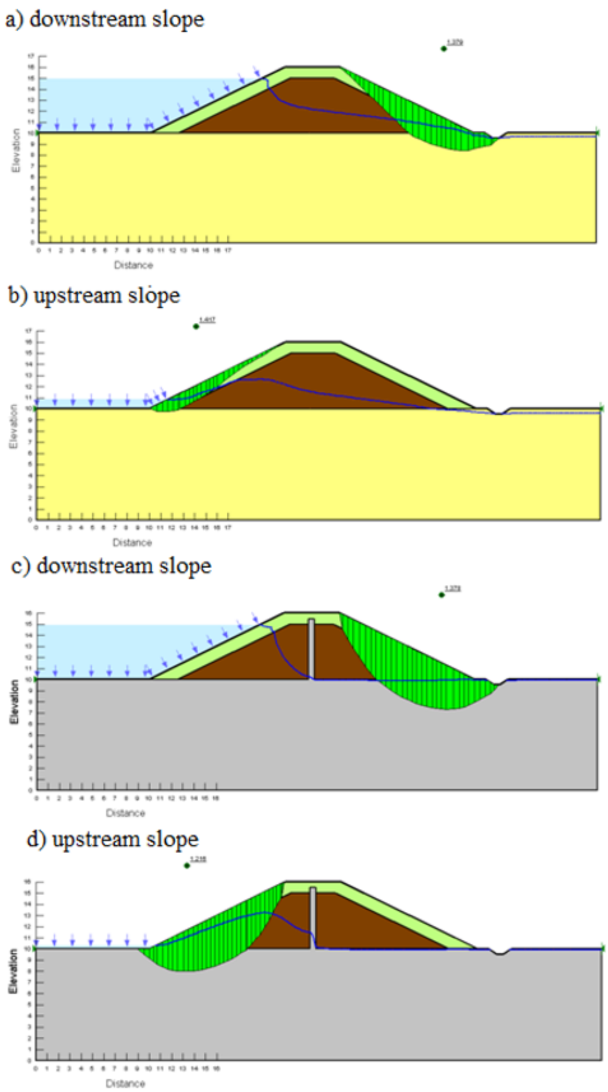


Fig. 4. General view of the slip surface for the embankment model with slope inclination of 1:2 for variant 1 (a, b) and variant 4 (c, d) of calculations.

4 Summary and conclusions

Based on the obtained results it was found that the studied colliery spoils are characterized by favourable values of geotechnical parameters for materials of this type and they meet the requirements for soil materials used in hydraulic constructions. First of all, these spoils are characterized by good compactibility, relatively low water permeability and average susceptibility to mechanical disintegration, which in the case of using this material for the construction of hydraulic embankments and using proper compaction technology, should reduce their susceptibility to weathering. The results of stability calculations for hydraulic embankments built of the studied spoils confirmed their suitability for that type of constructions, retaining the proper inclination of slopes, whereas the variant of embankment without sealing is safer from the stability viewpoint.

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