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Modeling of Permeability Flow in Embankments Formed from Ash-Slag Mixture

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1. Introduction

The construction of hydraulic embankments, in particular high ones and made of various soils, requires great experience. In the case of not properly chosen design parameters, there is a danger of structural deformations which occur due to subsiding, sliding, washing away or liquefaction the built-in soil [1, 11, 12].

Due to the shortage of natural soils for civil engineering purposes, heavy industry waste materials such as: furnace slag, dust, ashes and their mixtures are used for building embankments. However, in the case of hydraulic structures, industrial wastes require taking into consideration phenomena arising from the constant impact of water [16]. This is especially essential while erecting embankments that are supposed to be objects that lift water. Their proper design should ensure tightness and stability of the construction.

Modern compacting equipment and the appropriate controls of the quality of the executed works provide a means of economical dimensioning and quick erecting of embankments. Construction materials used nowadays, as well as the development of construction technologies, make it possible to use the soils previously useless for engineering – such as the above mentioned industrial wastes – for erecting structures of this type. The factor crucial to their usage is the optimization of the water lift height, which can be obtained by using proper drainage and filters as well as sealing elements in the subsoil and the body of the embankment.

Nowadays, geosynthetics are widely used in civil engineering. They perform both hydraulic (such as filtration, drainage, sealing) as well as mechanical functions (strengthening, separation and protection) [3, 5, 13, 15].

The synthetic materials play essential role in decreasing material and transportation costs in the construction engineering. They are used on larger and larger scale in domestic and world hydrotechnics [4, 14]. The wide use of plastics is caused by their favourable physical, mechanical and chemical properties. In some situations, their low unit weight is an advantage, too. It should also be emphasised that geosynthetics produced at present have much more advantageous properties when we consider ageing and biological resistance than the materials produced earlier. They are obtained by adding, in the production processes, special additives slowing down, to a certain extent, ageing processes. The popularity of polymers is starting to affect more and more both the design solutions of hydraulic structures and the technology of erecting them. Using plastics in hydraulic engineering brings major technological and economical benefits.

The research described in this paper is aimed to verify how the embankment which both lifts water and is made of the ash-slag mixture would behave and what possible kind of filter damage would occur at individual places of the structure. It was also verified whether the used kind of sealing and draining materials and the way of building them up would ensure save working conditions of the structure. In order to receive answers to these questions, two model embankments were examined – one made of the ash-slag only, the other one enriched by sealing and draining elements, characterised further in the paper.

2. Ash-slag mixture characteristics

The ash-slag used for building the model embankment was obtained from the Skawina Power Plant which produces electricity using hard coal and biomass as fuels.

For technological reasons, the biomass addition during combustion does not exceed 10%. The quantity of the so-called “green energy” (produced from biomass) comprises about 4% of the all produced electric power. The described ash-slag mixture is what remains after the burning process and accumulates in the bottom part of the furnace from where it is removed and ground mechanically. Determination of the physical parameters of the mixture used for constructing the models in the hydraulic channel was carried out in the laboratory of the Department of Hydraulic Engineering and Geotechnics of the University of Agriculture in Kraków.

Geotechnically, the ash-slag mixture can be characterised as silty sand with the content of the finest fractions f_{si+cl} = 24.87%. Basic geotechnical parameters of the material are shown in the Table 1.

Table 1. Geotechnical characteristics of the ash-slag mixture
Tabela 1. Charakterystyka geotechniczna mieszanki popiołowo-żużlowej

Parameter	Unit	Value
Fraction content acc. to PN-EN ISO 14688-1:2006 [10]: – gravel 2–63 mm – sand 0.063–2 mm – silt 0.002–0.063 mm – clay ≤ 0.002 mm	[%]	 19.36 55.77 22.38 2.49
Kind of soil acc. to PN-B-02481:1998 [9]	[–]	Po
Kind of soil acc. to PKN-CEN ISO/TS 17892-4:2009 [8]	[–]	siSa
Uniformity coefficient	[–]	14.71
Natural moisture content	[%]	40.83
Bulk density	[$g \cdot cm^{-3}$]	1.456
Dry density of solid particles	[$g \cdot cm^{-3}$]	1.078
Optimum moisture content	[%]	35.00
Maximum dry density of solid particles	[$g \cdot cm^{-3}$]	1.135
Permeability coefficient k_{10} (at I_S = 0.95)	[$m \cdot s^{-1}$]	$3.95 \cdot 10^{-6}$
Angle of internal friction at I_S = 0.95	[°]	36.0
Cohesion at I_S = 0.95	[kPa]	47.0

3. Model tests stand

The research stand was arranged in the hydraulic channel (Fig. 1), with inner dimensions: length – 600 cm, width – 100 cm, height – 120 cm. Inside the channel, the overflow partitions were placed which enabled any level regulation of upstream and downstream water, together with piezometric tubes which measured the water level inside the embankment model. The appropriate system of pipes and overflows enabled the regulation of inflowing water and the measurement of the water discharge flowing through the embankment.

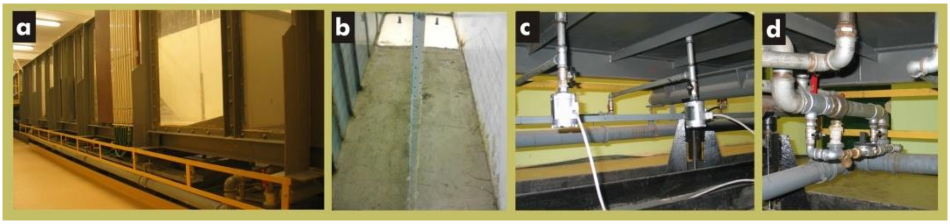

Fig. 1. Medium size apparatus for testing filtration through model embankments: a) a headwall view, b) the inside of the apparatus with the clayey bottom sealing, c) pressure transmitters for measurements of water level, d) measurement-and-spillway valves
Rys. 1. Średniowymiarowy aparat do badania filtracji przez modele nasypów: a) widok ściany czołowej, b) wnętrze aparatu z iłowym uszczelnieniem przydennym, c) przetworniki poziomu do odczytu zwierciadła wody w piezometrach, d) zawory pomiarowo-upustowe

4. Model tests method

Model embankments were built in the hydraulic channel by forming 10 cm thick layers, compacted mechanically to I_S = 0.95 (Fig. 2). After the models were constructed, the upstream water was lifted at the velocity of 10 cm/h, which made it possible to reach the highest level after 5 hours. Then, at twenty-four-hour intervals, water filtration discharge through the embankment q_{10} (m^3/s/mb) as well as water levels in piezometers installed at the horizontal distances of 50 cm were measured.

Fig. 2. Formation of a model embankment: preparation of the ground (a), formation and compaction of consecutive layers (b, c), the model before the boarding was taken off (d)
Rys. 2. Wznoszenie nasypu modelowego: przygotowanie podłoża (a), sypanie i zagęszczanie kolejnych warstw (b, c), model przed zdjęciem szalunków (d)

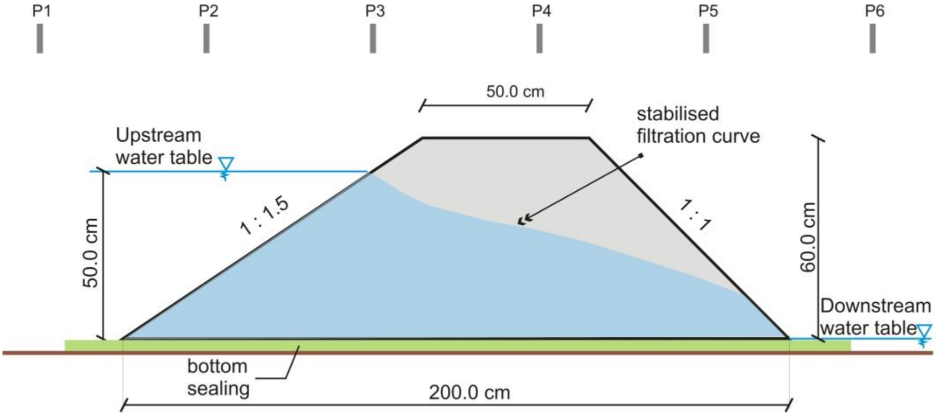

Fig. 3. Cross-section through the model embankment I (P1–P6 – piezometers)
Rys. 3. Przekrój poprzeczny prze model nasypu I (P1–P6 – piezometry)

The Figures 3 and 4 depict the cross-sections of the embankments and their dimensions. The conditions at which the tests were carried out, are presented in the Table 2. The models were made on the clayey subsoil 4.0 cm thick which replaced an impermeable layer. The measurements were continued until either the stabilisation of the filtration flow or the signs of the piping erosion ocurred. The measurements of the water level in piezometers were taken every 6 minutes. When the test was finished, the upstream water table was lowered and the behaviour of the upstream slope of the embankment was observed.

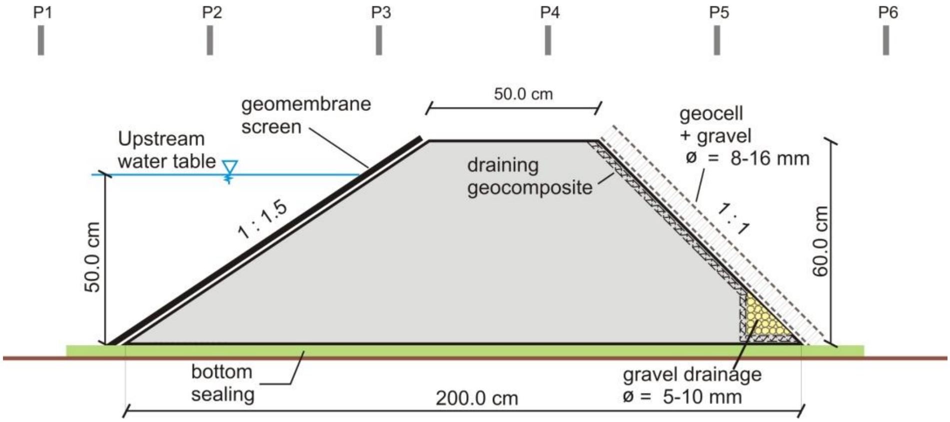

Fig. 4. Cross-section through the model embankment II (P1–P6 – piezometers)
Rys. 4. Przekrój poprzeczny prze model nasypu II (P1–P6 – piezometry)

Table 2. Technical characteristics of the tested models and testing conditions
Tabela 2. Charakterystyka techniczna badanych modeli i warunki badania

Model parameters	Unit	Model I	Model II
Compaction index (I_S)	[–]	0.95	
Difference in water levels (ΔH_{av})	[m]	0.50	
Hydraulic gradient (i)	[–]	0.35	
Duration of test	[days]	0.5	30
Volumetric flow rate Q_V	[cm^3/h]	1700–2500	0
Reason for the test stopping	[–]	increasing damage	flow stabilisation

5. Course of tests, results and analysis

5.1. Model I

In the model I, made of the ash-slag mixture only, the full lifting level was reached after 5 hours. After 8 hours and 20 minutes, the seeping water appeared at the foot of the downstream slope. The material of the downstream slope was moistened up to 15 cm above the model bottom, in some places it was also loosened and was beginning to liquefy. The tests of this model were completed after 12 hours and 30 minutes after the water lifting began, due to progressive destroying of the model which resulted from the removal of soil particles by filtering water (Fig. 5).

The courses of the filtration curves in the body of the model I (Fig. 3, 6) depict the phenomenon of water seeping through the embankment, which became the cause of the later damage.

The measurements, by means of three surface bench-marks installed on the crest of the embankment, showed no vertical displacements during the tests.

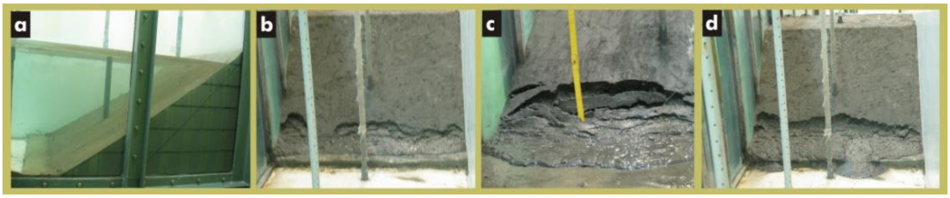

Fig. 5. The upstream slope – water level at 50 cm (a), damages of the downstream slope after 10, 11, 12 hours since the beginning of damming (b,c,d)
Rys. 5. Skarpa odwodna – piętrzenie na poziomie 50 cm (a), uszkodzenia skarpy odpowietrznej po 10, 11, 12 godzinach od rozpoczęcia piętrzenia (b,c,d)

The filtration curve, determined on the basis of the last measurement, is in effect a straight line cutting the downstream slope at the height of 15 cm. Its course indicates some hydraulic resistance of the ash-slag mixture in such dimensions of the embankment. The intersection of the filtration curve with the surface of the unprotected downstream slope caused washing away the material from its foot. The embankment material, due to its geotechnical parameters, underwent scouring very easily.

For downstream slope in model I, calculations were carried out using Bishop's method. The filtration curve in the embankment's body was determined on the basis of model tests in the hydrotechnical trough. The model defined in the calculations had dimensions ten times bigger than the physical model. For the clay in zone 1 (Fig. 7), the average norm parameters were assumed. Geotechnical parameters for the ash-slag mixture in zone 2 were determined in the laboratory and are presented in Table 1. In order to determine mechanical parameters for the ash-slag in zone 3, additional tests on cohesion and angle of internal friction were carried out "under water". Tests were carried out in a standard direct shear box apparatus in boxes that were 12 × 12 cm in cross section. The obtained values of angle of internal friction were practically the same – 36°. However, the value of cohesion was a few times lower – 9,8 kPa.

With reduced strength parameters, the safety factor was 0,18 (Fig. 7). If we assume the value of the safety factor above 1, the cohesion should be higher than 9,8 kPa (Fig. 8), whereas for the angle of internal friction, values higher than 1° will be enough.

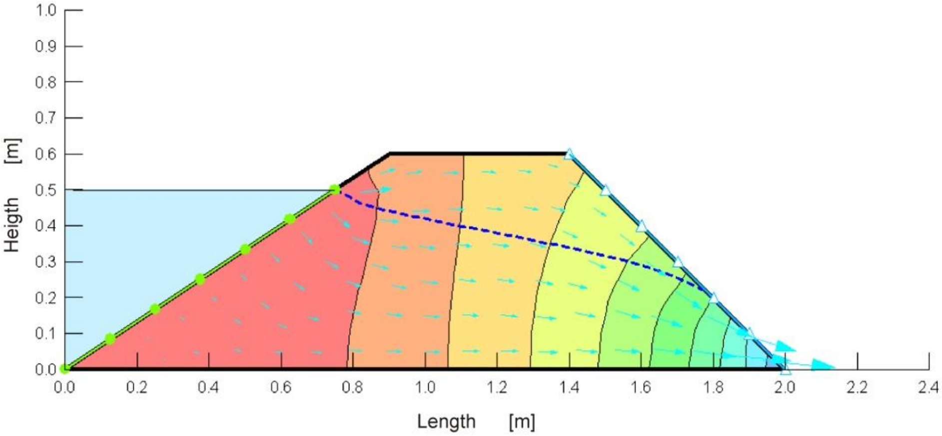

Fig. 6. Calculation permeability flow in model I
Rys. 6. Obliczeniowy przepływ filtracyjny w modelu I

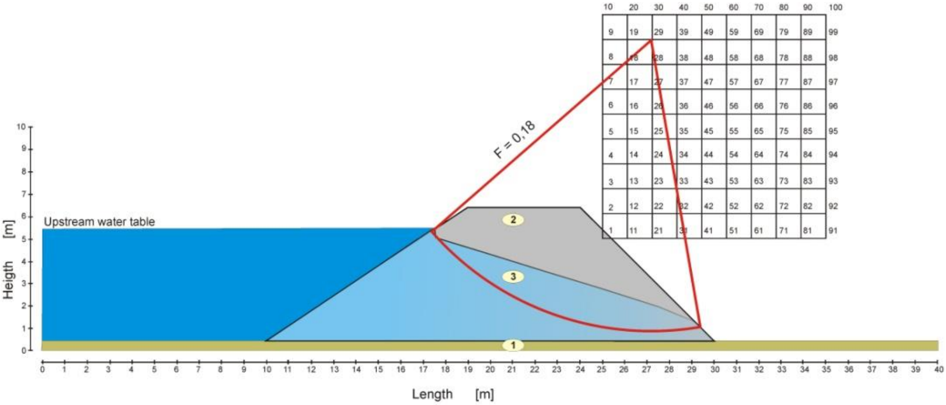

Fig. 7. Calculation scheme for downstream slope stability in model I
Rys. 7. Schemat obliczeniowy stateczności skarpy odpowietrznej modelu I

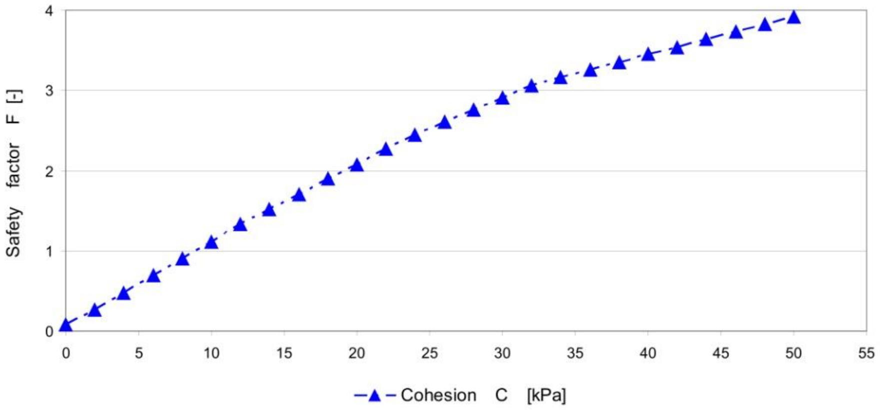

Fig. 8. Relationship between the safety factor and the cohesion
Rys. 8. Zależność współczynnika bezpieczeństwa od wartości spójności

5.2. Model II

The model II was built using the analysis of the filtration damage in the model I and by means of introducing sealing and draining elements. The upstream slope was lined with a 2.0 mm thick geosynthetic polymeric barrier GBR-P smooth at both sides (Fig. 9a). The geomembrane was built up in order to seal the embankment and protect the upstream slope from water erosion. Geomebranes can work in direct contact with mineral and anthropogenic soils. It is important to keep the graining criterion for the adjoining soil, as the grain shape for coarse-grained soils has an impact on a form and a number of damages. In case of installations on slopes, the coefficient of friction between soil and geosynthetic is checked [2, 6, 7].

The draining geocomposite supplemented (Fig. 9b) with the gravel drainage of the triangle cross-section 15 × 15 cm at the foot was laid on the surface of the downstream slope. The whole surface of the slope was covered with the cellular geosynthetic (Fig. 9c) and gravel of the granulation 8–16 mm (Fig. 9d).

After 5 hours of water lifting at the upstream stand, the target level of 50 cm was reached. The water level in piezometers was read every 6 minutes. When the water level stabilised, the readings were taken every 24 hours and potential leakages were checked. The used geosynthetic polymeric barrier proved to be completely impermeable for the lifted water.

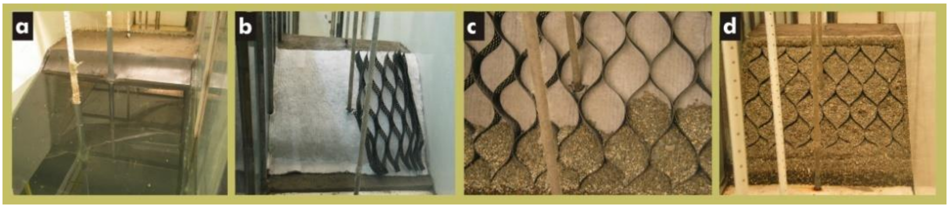

Fig. 9. The upstream slope protected with the geomembrane – water level at 50 cm (a), placing drainage elements on the downstream slope (b, c, d)
Rys. 9. Skarpa odwodna zabezpieczona geomembraną – piętrzenie na poziomie 50 cm (a), układanie elementów drenażowych na skarpie odpowietrznej (b, c, d)

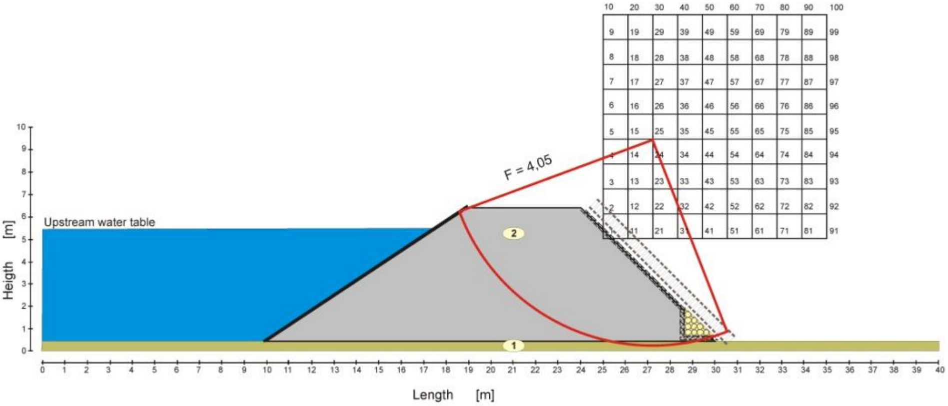

Fig. 10. Calculation scheme for downstream slope stability in model II
Rys. 10. Schemat obliczeniowy stateczności skarpy odpowietrznej modelu II

Figure 10 shows the calculation scheme for the downstream slope stability in model II. For clay in zone 1 norm parameters were assumed. Geotechnical parameters of the ash-slag mixture in zone 2 are presented in Table 1. After placing the geomembrane, embankment's soil remains unsaturated. It has high values of cohesion and angle of internal fraction. Drainage elements add load on the downstream slope only to a small extent. Geotechnical parameters of the ash-slag mixture and the embankment geometry allow to obtain the safety factor above 4.

6. Conclusions

The carried out tests, calculations and the results obtained from the analysis provided the basis to formulate the following conclusions:

1) The ash-slag mixture, due to its geotechnical parameters, should not be used for erecting hydraulic embankments without proper reinforcement and sealing.
2) The main damage in the model I was caused by washing away the soil particles from the foot of the downstream slope by the filtrating water. The upstream slope did not show any significant damage, even after the rapid drawdown of the upstream water surface.
3) The course of filtration curves in the models, determined on the basis of the piezometric levels measurements, proved that they worked as they were supposed to in the tests.
4) Tests and calculations gave results that were compatible with regard to the lack of stability at the full damming in model I. Many factors contributed to this situation. The main is water, which is infiltrating into the embankment's body, causing its washing out and, as a result, the damage to the downstream slope.
5) The used GBR-P geomembrane blocks the water flow in the embankment as well as protects the upstream slope from its being washed away. Building it up in a form of a screen in the downstream slope of the embankment can be a sealing treatment for renovated or newly erected embankments.
6) Building the gravel drainage at the foot of the downstream slope prevents suffosion and liquefaction. Using the draining geosynthetic and cellular system filled with gravel in the downstream slope, stabilises it and prevents liquefaction.

The results of the carried out model tests give grounds for predicting how the ash-slag embankment may co-function with geosynthetics. Dimensions of embankments cross sections, a lifting level, and values of hydraulic gradients are usually much more beneficial in practise than those assumed in the model tests. That is why the results that have been presented have a big safety margin in relation to the expected values in real life situations.

The issue of the influence of geosynthetics, built in the hydraulic embankment, on the filtration flow through these structures is significant and up-to-date in view of the growing need to construct objects using this technology.

The tests of filtration through the embankments models made in semi-technical scale are performed sporadically due to their labour intensity. Their results describe most accurately the phenomenon of filtration through the natural embankments. The models show the possibility of building-in additional elements, such as sealing, drainage as well as installing the measuring equipment.

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Modelowanie przepływu filtracyjnego w nasypach z mieszanki popiołowo-żużlowej

Streszczenie

Z uwagi na deficyt gruntów naturalnych w budownictwie lądowym do budowy nasypów stosuje się materiały odpadowe z przemysłu ciężkiego, takie jak: szlaka wielkopiecowa, pyły, popioły, żużel oraz mieszanki tych materiałów. Jednak w przypadku budowli hydrotechnicznych zastosowanie odpadów przemysłowych wymaga uwzględnienia zjawisk wywołanych stałym oddziaływaniem wody. Jest to szczególnie istotne w przypadku wykonywania nasypów mających pełnić funkcję budowli piętrzących wodę. Podstawą prawidłowego zaprojektowania tego typu obiektu jest zapewnienie szczelności oraz stateczności wykonanej konstrukcji. Artykuł przedstawia wyniki badań modelowych dwóch wykonanych w skali zmniejszonej modeli nasypów – jeden został zbudowany tylko z mieszanki popiołowo-żużlowej, drugi wyposażono w ekran uszczelniający i elementy drenujące.

Badania wykazały, że odpad paleniskowy bez odpowiednich zabiegów nie może być wykorzystywany w budownictwie wodnym. W przypadku zawodnienia mieszanki popiołowo-żużlowej zmniejsza się kilkukrotnie wartość spójności. Obliczony współczynnik bezpieczeństwa i wyniki badań modelowych są zbieżne w kwestii wystąpienia utraty stateczności. Należy więc zmniejszyć możliwie skutecznie dopływ wody do korpusu na przykład przez wbudowanie w odpowiednich miejscach nasypu geosyntetycznych elementów uszczelniających i drenujących, zapobiegających zjawiskom sufozji i upłynniania.