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ANALYSIS OF THE STABILITY OF THE SLOPE OF THE HYDRAULIC EMBANKMENT MADE OF THE ASH-SLAG MIXTURE

1. Introduction

Coal combustion waste, which is produced in power plant furnaces and takes, among others, the form of the ash-slag mixture. Owing to the mass production of this material, it is currently used for building different earth structures — as a valuable anthropogenic soil. Good compactibility of this kind of waste mean, that it is often used for building embankments (including hydraulic ones). The condition for using the ash-slag mixture for such types of structures is its careful protection against water influence. Improperly chosen design parameters can lead to the loss of the stability of the slopes of the erected structure [4, 5, 12, 13].

The construction of hydraulic embankments requires great professional knowledge both in the scope of construction, as well as properties of soil materials [1, 8, 11]. The necessary conditions for using the combustion waste as a building material is its verification, whether a given mixture is suitable for this purpose. Prior to using the waste, a range of tests should be conducted — first laboratory and then model ones. Results are not always reliable, therefore they should be repeated several times and the physical model tests should be compared with numerical models.

The tests described in the paper are aimed at determination of the relationships between the location of the depression curve in the body of the hydraulic embankment, geotechnical parameters of the saturated ash-slag mixture and the obtained value of the stability index.

2. The ash-slag mixture characteristics

The material for model tests came from the Skawina Power Plant. It is coal combustion waste, as hard coal is the main fuel in this power plant. Due to legal requirements, during

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combustion, a ten-percent addition of biomass is applied in the form of sawdust, sunflower pellet and cereal seeds. The ash-slag mixture accumulates at the bottom of a furnace, from where it is removed and mechanically ground.

The physical and chemical properties of combustion wastes are very diverse — they depend on properties of the used fuel, combustion technology, way of transport and storage. The determination of physical and mechanical parameters of the used mixture — indispensable for building a proper model in a hydraulic channel — were carried out in the laboratory of the Department of Hydraulic Engineering and Geotechnics of the University of Agriculture in Kraków. The basic geotechnical parameters of the tested material, which may be characterised as silty sand (siSa) with the content of the finest fractions f_{si+cl} = 24.87% [6], were set together in the Table 1.

TABLE 1
Geotechnical characteristics of the ash-slag mixture

Parameter	Unit	Value
Fraction content acc. to PN-EN ISO 14688-1:2006 [9, 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 [7]	[—]	Po
Kind of soil acc. to PN-EN ISO 14688-1:2006 [9, 10]	[—]	siSa
Uniformity coefficient	[—]	14.71
Natural water 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
Angle of internal friction at IS = 0.95	[°]	36.0
Cohesion at IS = 0.95	[kPa]	47.0

3. Model tests stand

The hydraulic channel (Fig. 1), where the research stand was arranged, is a structure 600 cm long, 100 cm wide and 120 cm high (all values are the inner dimensions). Inside the channel, there overflow partitions were installed, making possible any level regulation of upstream and downstream water, as well as piezometric tubes for measurements of the water level inside the model. System of pipes and overflows enabled the regulation of inflowing water and the measurement of the water discharge [2].

Fig. 1. Hydraulic channel — Medium size apparatus for testing filtration through model embankments

4. Model tests method

The model embankment was built in the hydraulic channel by forming 10 cm thick layers, compacted mechanically to $I_S = 0.95$ (Fig. 2). The model was made on the clayey subsoil 4.0 cm thick, which substituted for an impermeable layer. After forming the model according to the assumed dimensions (Fig. 3), lifting up upstream water was carried out at the velocity of 10 cm/h, which made it possible to reach the full level after 5 hours. During the lifting up, the water level at the upper stand and the level of the filtration curve inside the channel was being recorded. The measurements were taken until the visible signs of the piping erosion occurred. Then, after completing the test, the upstream water table was lowered and the behaviour of the upstream slope was observed.

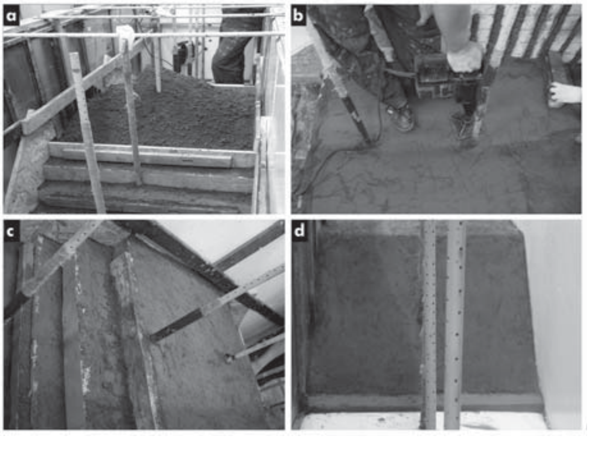

Fig. 2. Erecting the model embankment: a) pouring the weighed out amount of the ash-slag on the soil layer, b) mechanical compaction, c) model before sloping, d) model after sloping

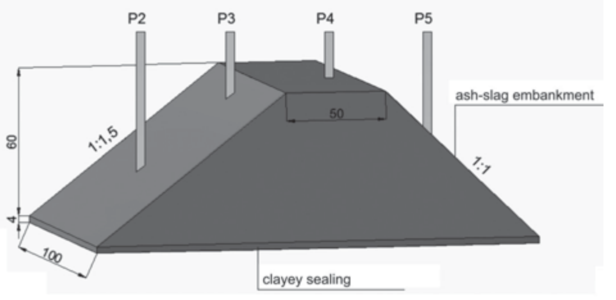

Fig. 3. Scheme of the physical model of the embankment (P2–P5 – piezometers) [3]

The range of lifting-up levels, applied in the course of the conducted tests, was equal 0.00–0.50 m. The values of the hydraulic gradient for the individual calculation variants fell in the range from 0.05 to 0.35. The test lasted several hours and could not be prolonged owing to the increasing filtration damage of the downstream slope.

5. Analysis of the slope stability

The analysis of the stability of the downstream slope was performed numerically using the Bishop's method. The computer model defined in the calculations had dimensions ten times greater than the physical model built in the hydraulic channel. The bottom sealing with the clayey layer was taken into consideration, the layers in the body of the embankment were marked out below and above the filtration curve. The geotechnical parameters of the ash-slag mixture were taken from the tests performed in the laboratory of the Department of Hydraulic Engineering and Geotechnics. The assumption for the computations water table levels in the body of the embankment were determined in the model tests in the hydraulic channel. The calculations of the stability index were carried out for six schemes differing with the height of damming level and the location of the filtration curve in the body of the embankment.

The scheme in the figure 4a shows the state before the lifting up water — the material and dimensions of the embankment make impossible obtaining the stability index bigger than 4, which classifies the downstream slope as the self-stable one.

The schemes in the Figure 4b-e depict the state in the process of lifting up and stabilising the free-surface water level at the upstream stand and the filtration curve in the body of the embankment. At the damming level equal to 10 cm (Fig. 4b), which was reached after 1 hour, the piezometric measurements showed the slight moistening the embankment body. The result of the calculation of the stability index made it possible to regard the downstream slope as self-stable at the value of F = 4.04. The damming levels: 20 and 30 cm of (Fig. 4c and 4d) were reached respectively after 2 and 3 hours. In these cases, the volume of the embankment soil in the saturation zone was not great, the observation of the physical model did not reveal seeping water through the em-

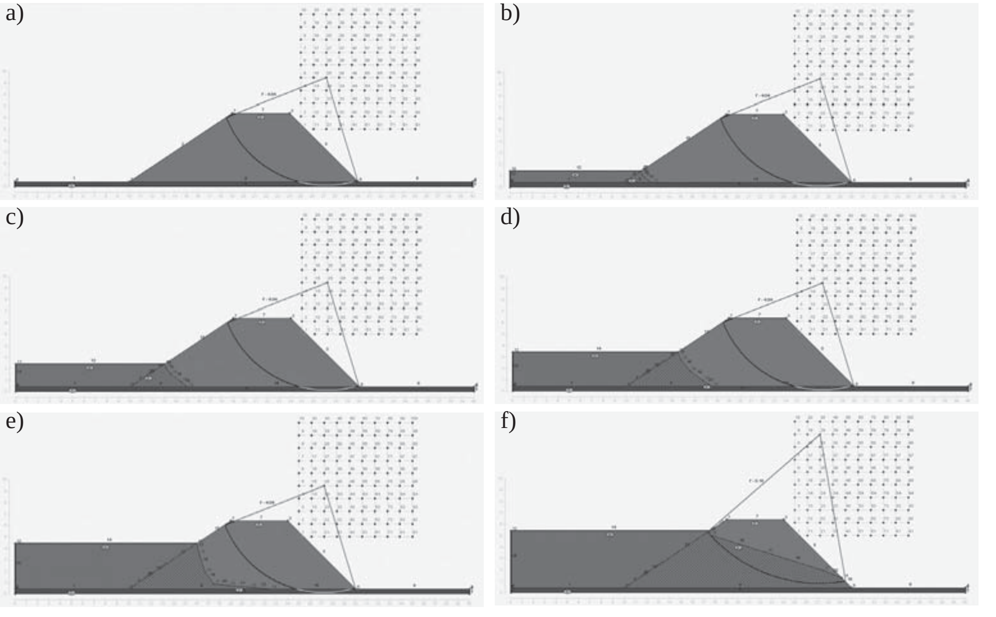

Fig. 4. Sliding curves for the individual calculation schemes before lifting up water (a), at the damming level equal to: 10 cm (b), 20 cm (c), 30 cm (d), 40 cm (e), 50 cm (f)

bankment body. The calculations of the stability index value were still very favourable, amounting in both cases above 4. The damming level of 40 cm (Fig. 4e) was reached after 4 hours. The course of the filtration curve, determined on the basis of the piezometric measurements, proved that the volume of the aerated soil zone still prevailed in the embankment. The observation of the downstream slope surface did not show the possibility of filtration of water through the embankment body. The calculated stability index still remained about 4.

The target damming level (Fig. 4f) was reached after 5 hours. The seeping water appeared at the foot of the downstream slope after 8 hours and 20 minutes. Determined on the basis of the piezometric measurements, the stabilised level of the filtration curve was practically a straight line, crossing the downstream slope at the height of 15 cm. The course of this line indicated little hydraulic resistance of the ash-slag mixture at these dimensions of the embankment. The intersection of the filtration curve with the surface of the unprotected downstream slope caused washing away the material from the foot of the physical model slope. The embankment material, owing to its geotechnical parameters, very easily underwent scouring.

The calculated stability coefficient for the case 6 – at the reduced strength parameters $ø$ and c – was equal 0.18., Determined using back analysis method, the values of mechanical parameters at which it is possible to obtain the value of the stability coefficient greater than 1.3 are: the angle of internal friction – 8° and cohesion – 8 kPa.

6. Summary

At the lower levels of lifting up water, the hydraulic embankment of the assumed dimensions made of the ash-slag is a stable structure. The situation deteriorates at high damming, which results in a high course of the filtration curve at the unfavourable value of the hydraulic gradient. The performed tests and the calculations carried out give compatible results on the issue of the lack of the model stability at the full damming. Many factors influence this situation. The main factor is water, which by infiltrating into the centre of the embankment body causes its entrainment and as a consequence damage to the downstream slope. The next factor, the small bulk density of the soil, is very unfavourable in the case of the soil working under water. The calculated value $F = 0.18$ reflects the physical model behaviour. The downstream slope material, moisturized up to 15 cm from the foot, became loosened and started to liquefy, the scouring was observed.

Phenomena of the water filtration tested in the embankment models made in the half--technical scale are most similar to the filtration processes through natural embankments. The results of such tests can give information on the expected course of work to embankments made of the ash-slag or other soils with similar geotechnical parameters. These kinds of models give the possibility of watching the filtration phenomena — even of the critical ones — without concern for the consequences of the entire test. An asequent landslide, which started to arise, is one of the simplest cases — it occurres in homogenous, non-stratified soils, the slip surface is approximately of a circular cylindrical shape. The rising water infiltrates into the slope and gradually saturates the embankment body, reducing the strength parameters of the sol in the saturation zone. However, it is worth noting, that the dimensions, damming levels and hydraulic gradients applied in practice while building the embankments are usually much more beneficial than the ones accepted in the model tests described.

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