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Selection Activity Optimization for a Geotextile-Ash System from Filtration Function Point of View

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SELECTION ACTIVITY OPTIMIZATION FOR A GEOTEXTILE-ASH SYSTEM FROM FILTRATION FUNCTION POINT OF VIEW

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ABSTRACT

The paper presents a complex study concerning the fly ash deposits. It is known that the fly ash is an industrial by-product which is stored in landfills, with important implications on the environment.

On this line, the general stability problem under different hydraulic and mechanical conditions was studied. Experimental and numerical analysis results are presented.

The paper is about a fly ash embankment protected against erosion with different geotextile types. In order to obtain the main parameters of this compatibility problem, before performing a numerical analysis, some laboratory tests were undertaken.

Conclusions were drawn regarding the optimum geotextile-fly ash filtration system to be used in such structures.

INTRODUCTION

Fly ash is a by-product produced by the burning of pulverized coal in thermal power plants. Usually, the fly ash is stored in ash ponds and ash dikes. In the case of ash ponds, the ash is deposited wet, in the form of slurry, due to economical reasons. If the process of ash settling is not taking place at a rapid pace, then some problems may occur regarding the drainage of the structure. The second storage possibility is the dry disposal of fly ash, in structures called ash dikes. A very important aspect concerning these types of embankments is their stability. This depends directly on the efficiency of the drainage system. A poor dike stability can lead to various environmental problems, such as local roadways blocking, habitat damages, human health jeopardizing etc.

The internal seepage taking place within the ash dike must be controlled by using adequate filters in order to hold solid particles and also to allow water to pass freely. The traditional method used for achieving the drainage and filtration functions consists of constructing a rock toe and a sand blanket. The more modern approach is to install a drainage geocomposite material at the toe of the dike or perforated plastic pipes covered in a geotextile. In both cases, the geotextile acts as a cover with multiple functions: protection, filtration and separation.
The scope of this study was to evaluate different aspects of stability concerning an ash containment dike and to draw conclusions about the proper remedial measures to be taken, thus avoiding a number of unpleasant consequences.
The paper deals with various aspects regarding the proper design of a fly ash dike:

- a proper selection of the materials used in the structure; laboratory tests were done in order to determine the fly ash properties, as well as the characteristics of the ash-geotextile system for different types of geotextiles; the most appropriate geotextile to be used in such structures was selected for further investigations;
- the importance of a properly designed drainage and filtration system was emphasized be performing a stability analysis study of a proposed ash embankment; the analysis was conducted using Geostudio software, namely SEEP/W and SLOPE/W; a comparison was made between the situation with the drainage blanket and the one without it in terms of FOS (factor of safety); the importance of a drainage system presence was emphasized.

MATERIAL PROPERTIES AND SELECTION

Fly ash

General description. The fly ash used in this study comes from a locality in Romania called Rovinari (Fig. 1), situated in Gorj county. The city is located 25 km southwest of the Targu Jiu municipality, being connected to it through the national road DN 66 (part of the European route E79).

Fig. 1. Rovinari location in Romania. (http://ro.wikipedia.org/wiki/Rovinari)

Its economy is based on mining activities, one of the largest thermal power plants in Europe being located here, thus generating several ash deposits in the area around it (Fig. 2). The main mineral resource of Rovinari is inferior coal (lignite), used as fuel in the power plant.

Fig. 2. Fly ash deposit near thermal power plant.

Properties. The key property needed for an accurate stability analysis with SEEP/W is the hydraulic conductivity (permeability) of the materials used in the structure. For SLOPE/W, the important values to be introduced in the program are the unit weights and shear strengths characteristics.

The fly ash permeability was determined to be k = 1.7x10-5 m/s = 1.7x10-3 cm/s, by using the variable head permeameter, according to Romanian Normative STAS 1913/6-76.

In addition to the coefficient of permeability, other fly ash characteristics were needed for the numerical modeling of the structure, such as the unit weight and shear strength. These properties were determined through density and direct shear testing in the laboratory, as well as through mathematical relations.

The unit weight of the dry ash resulted γ_d = 8.9 kN/m^3 by weighing and the specific unit weight, γ_s = 23 kN/m^3, by pycnometer testing. The following relations were used for calculating the unit weight of the saturated ash, γ_{sat}:

$$\gamma_d = \gamma_s(1-n) \tag{1}$$

$$\gamma_{sat} = \gamma_d + n \cdot \gamma_w \tag{2}$$

, where: n = porosity (%)

γ_w = unit weight of water (γ_w = 10 kN/m^3)

A correct evaluation of the shear strength is key to obtaining truthful stability results. The shear strength is defined in respect to the Mohr-Coulomb failure criterion.

$$\tau = \sigma tg\phi + c \tag{3}$$

, where: τ = shear strength (maximum possible value of shear stress) - (kN/m^2)

σ = normal stress (kN/m^2)

ϕ = total stress friction angle (°)

c = cohesion (kN/m^2)

The cohesion values signify that the soil has a certain tensile strength.

The shear strength characteristics of fly ash were determined by using a direct shear equipment and the diagram presented in Fig. 3 resulted. An area defined by the minimum and maximum shear strengths values was generated and an array of shear parameters was chosen for further investigation, in order to cover most of the possible values to be encountered in such structures: c = (2.5; 5) kPa and tgϕ = (0.1; 0.2; 0.26; 0.3).

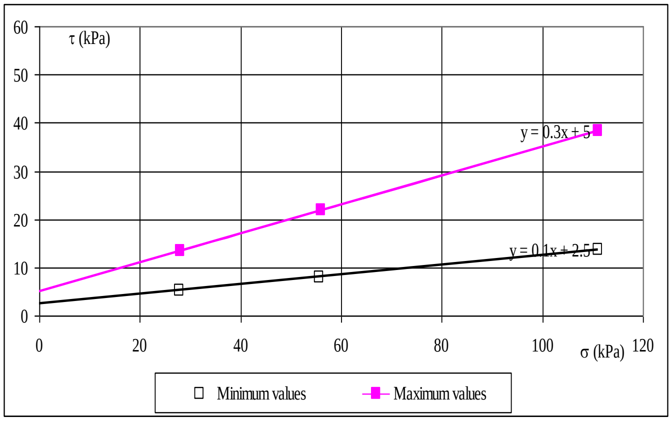


Fig. 3. Shear strength diagram for ash.

Geotextile properties

The properties of the geotextile chosen for this study are summarized in the table below. The main characteristics that needed to be fulfilled by it were excellent filtration capacity and reduced or null risk of potential clogging during lifetime. The material was tested and chosen as most suitable to be used in contact with fly ash structures in a previous paper by Chirică and Taloş (2012).

Table 1. Properties of tested geotextiles

Structure	Mass/ area	Pore opening size	Thickness	Porosity	Permeability
-	g/m^2	mm	mm	%	m/s
PET*, nw,np	1000	0.07	5.47	85.4	$3.9x10^{-3}$

GTX = geotextile, PP = polypropylene, PET* = recycled polyester, nw = nonwoven, np = needle-punched, c = calandered.

All the properties from the table are from the manufacturer, except for porosity, which was determined with the Wayne and Koerner (1993) formula.

STABILITY ANALYSIS

Methodology description

For a better understanding of the ash dike's loss of stability, the Geostudio software program was used, a modelling program developed by GEO-SLOPE International Ltd. in Calgary, Canada. Geostudio contains different models of numerical modeling, suitable for different applications. In this study, the SEEP/W and SLOPE/W programs were used in order to simulate the process of slope failure and to be able to compare the initial situation to the one with proposed remedial measures.

Firstly, a fly ash dike model was proposed for the stability analysis study. This structure is presented in Fig. 4. The water level was considered to be at a height of 3m from the dike base, representing the elevation of the ash pond (the saturated ash) stored at the base of the structure.

There are several aspects needed to be taken into consideration when analyzing the stability of a slope. These include the knowledge of material properties, the application of theoretical concepts and empirical relations, as well as computational modeling methods. A shear failure involves sliding of an area of the dike or the dike and its foundation. In this case, the slipping is considered to occur along the downstream surface of the dike, the most likely critical situation.

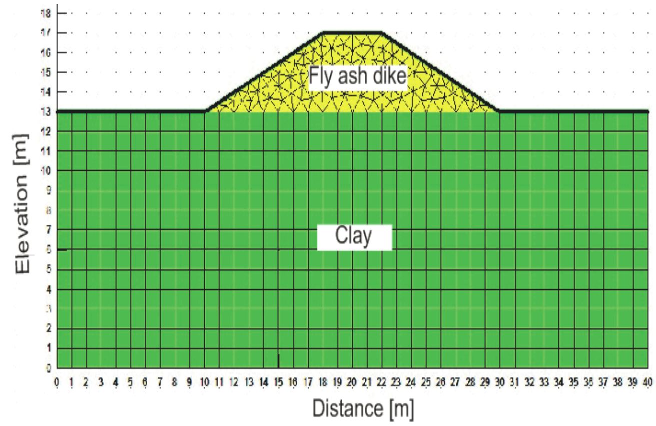


Fig. 4. SEEP/W model of regions.

In the following chapters there are briefly presented the software programs used in this study and also the requirements needed to simulate the field conditions.

SEEP/W modelling. SEEP/W was used in this study to simulate the water seepage through the dike structure. This numerical modeling software program simulates the groundwater regime through a material. The boundary conditions and material properties are introduced as input data.

First of all, the boundaries for each material were set by using the "Draw Regions" command. This way, each region created has its own physical properties, which are introduced afterwards. Two distinct regions were defined, one containing the clay subsoil and the other one, the fly ash forming the dike.

In SEEP/W analysis, the only property needed to define these materials was the permeability coefficient. The ash permeability was determined through the previous laboratory testing and has a value of $k = 1.7x10^{-5}$ m/s, and a permeability of $k = 10^{-8}$ m/s was considered for clay, a common value from geotechnical investigations. Constant head boundaries were applied for the submerged surfaces of the structure. The bottom clay was considered to be an impermeable layer by specifying a total flux of zero along this boundary.

The upstream face of the dike, situated in the left, was considered to have a total head boundary condition of 16m, corresponding to the elevation of the ash pond (the saturated ash) along the upstream face. The downstream face of the dike, situated in the right, had a total head boundary condition of 13m. An impermeable boundary was set along the base of the dike for defining the water flow domain. The difference in water head between the two faces of the dike led to the generation of the water depression curve inside the structure (Fig. 5). This allows for pressure heads to be identified at any location within the dike. In the situation with drainage system at the base of the dike, the depression curve shifts to the bottom of the dike, at the start point of the drainage blanket inside the dike.

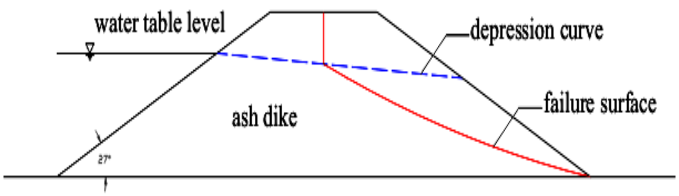


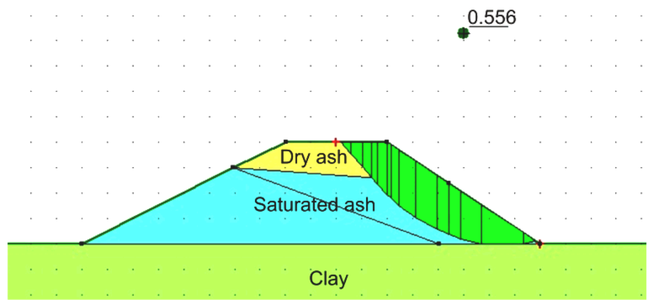
Fig. 5. Structure of ash dike.

By using the SEEP/W tutorial, mesh surfaces were created as equilateral triangles or squares, in order to obtain a truthful finite element calculation.

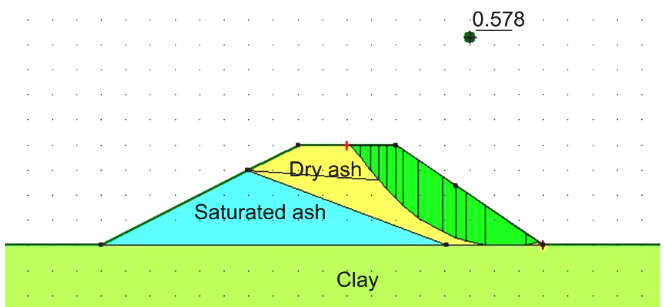
<u>SLOPE/W modelling</u>. Geostudio software suite allows the user to import data from one program to another, thus enabling a complex analysis of the studied phenomenon. The SLOPE/W feature of Geostudio was used to import the data regarding the region geometry and pore water conditions from SEEP/W, allowing the slope stability calculations to be made. The analysis type used in this program was based on the Morgenstern and Price method, due to the fact that it represents one of the most complex Limit Equilibrium Methods (LEM), by considering all the forces between slices.
The input data consisted in unit weight, friction angle and cohesion for each material.
Two different situations were considered in this study:

- the initial stage, without the drainage blanket
  - in this case, three different regions were defined with distinct parameters: the clay region, with γ = 21 kN/m^3, ϕ = 19°, c = 40 kN/m^2; the dry ash region, with γ = 12.8 kN/m^3, and the saturated ash region, with γ = 15 kN/m^3; both ash regions were studied for different values of friction angle and cohesion, ϕ = (6; 11.3; 14.6; 16.7)°, corresponding to values of tg ϕ = (0.1; 0.2; 0.26; 0.3), and c = (2.5; 5) kN/m^2; these values were proposed considering previous research on ash;
  - the critical long slip surface was considered in this analysis, thus generating the lowest possible FOS value for the proposed structure.
- the final stage, with the drainage blanket at the base of the dike
  - in this case, three different regions were created as well, but the area comprising the saturated ash diminished in favor of that with dry ash, because of the depression curve shifting towards the drainage blanket; as seen in Fig. 10; all regions kept the same parameter values, and the same range of values as in the first stage was considered;
  - the same critical slip surface was defined as in the first step; the FOS values obtained were compared to the initial ones.

An example of slope failure modeling of the proposed dike for both cases – with and without drainage system is illustrated in Fig. 6, for c = 2.5kPa and tgϕ = 0.1.



a)



b)

Fig. 6. Detail of slope analysis modeling for c = 2.5kPa and tgϕ = 0.1 – a) without drainage system; b) with drainage system.

<u>Discussion and results</u>

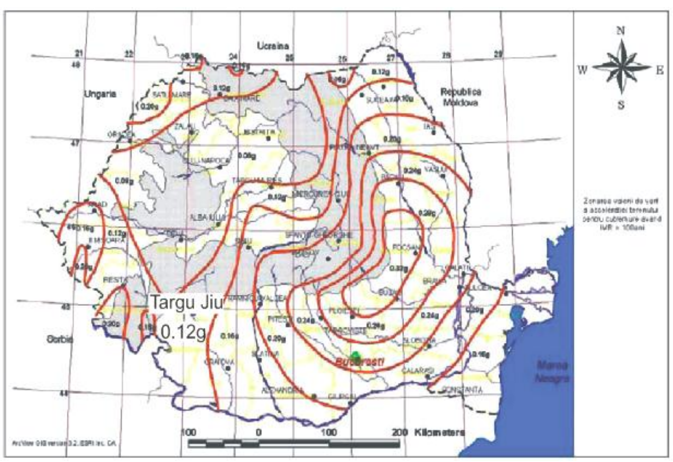
Proper FOS values are required in order to ensure a good long-term performance of slopes. The value of the calculated FOS obtained by modeling depends on the design parameters chosen to be defined in the analysis, e.g. unit weights, cohesion and friction angle. The admissible values of FOS are established for different types of structures, based on regulations and experience. FOS values resulting from the numerical modeling of the two situations are summarized in Table 2. An increase in FOS is observed for the final stage, due to applying the remedial measure with drainage blanket.

Table 2. FOS values with Fellenius method for initial and final stage

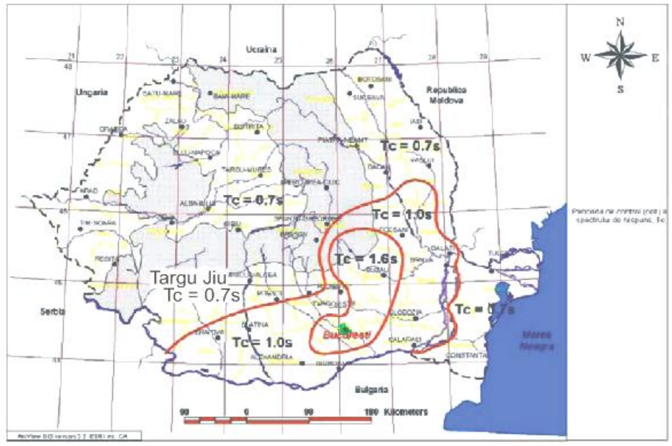
Shear strength properties	Initial stage	Final stage
	FOS	
c=2.5kPa		
tgϕ = 0.1	0.556	0.578
tgϕ = 0.2	0.757	0.773
tgϕ = 0.26	0.877	0.895
tgϕ = 0.3	0.956	0.972
c=5kPa		
tgϕ = 0.1	0.885	0.933
tgϕ = 0.2	1.092	1.135
tgϕ = 0.26	1.221	1.264
tgϕ = 0.3	1.303	1.346

Analysis of the results presented in the table above also took into account the seismic zoning of Romania. According to Romanian Normative P100/1-2006 for seismic design activity, the Romanian seismic areas maps from Fig. 7 were used in order to determine the seismic parameters' values. These were found as follows:

- the seismic hazard depending on the peak value of horizontal ground acceleration a_g (determined for the average value of the recurrence interval IMR = 100 years corresponding to the ultimate limit state) has a value of $a_g = 0.12g$;
- the control period T_c of the response spectrum for the analyzed area is of 0.7s.



a)



b)

Figure 7. Romanian seismic map in terms of : a) ground acceleration ag for earthquakes with IMR = 100 years; b) control period Tc of the response spectrum, acc. to P100-1/2006.

From the seismic maps it can be observed that, for the analyzed area, $a_g = 0.12g$ m/s^2, resulting a horizontal seismic coefficient $c_h = 0.12$ m/s^2 and a value of $c_v = 0.5c_h = 0.06$ m/s^2 for the vertical seismic coefficient. A ratio of FOS in static and seismic conditions was determined by using Eq. 4.

$$\frac{FOS_s}{FOS} = \frac{1}{1 + c_h ctg\,\alpha + c_v} \qquad (4)$$

, where: FOS_s = factor of safety in seismic conditions
FOS = factor of safety in static conditions
α = angle between the tangent to maximum slip area curvature and horizontal
c_h, c_v = seismic coefficients on horizontal and vertical, respectively

The forces acting on the slope are illustrated in Fig. 8.

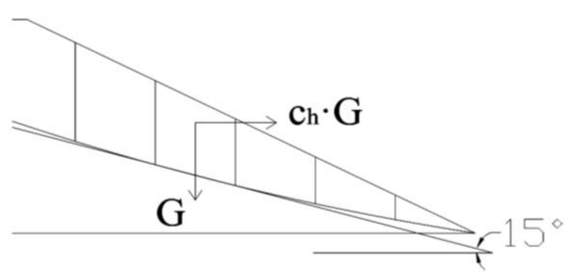


Fig. 8. Typical seismic forces acting on the slip surface.

From the seismic force equilibrium, an angle α = 15° resulted, thus obtaining a ratio FOS_s/FOS = 0.66. Therefore, a minimum FOS of 0.66 is required in seismic conditions. As a result, a FOS value higher than 0.66 is needed in static conditions for ensuring the dike's stability. From practical experience, a FOS value lower than 1 is considered dangerous for practical engineering, signaling the slope's instability, and a FOS value higher than 1 means that the slope is stable. In the first case, measures for increasing the FOS are in order, such as drainage systems and buttress at the base of the slope. The importance of an efficient drainage system selection is being stressed, a system composed by a geotextile used as filter and a geonet or plastic pipes for ensuring water transmissivity.

Verification calculus

Computer programs allow a detailed analysis of slope stability, but it is common practice to perform a verification of the results, in order to confirm that the lowest FOS had been calculated. In this case, a calculation program called STAB-1 was used, first described by Athanasiu et al. (1983). STAB-1 allows a slope stability analysis by means of the shear parameters envelope for limit equilibrium (FOS = 1). Sliding is considered to take place on a predetermined surface of ordinary shape.

STAB-1 algorithm is based on a graphic-analytical version of the Fellenius Method, also known as The Ordinary Method of Slices (OMS). The slices are defined by a number of straight lines across the potential slip surface. In this method, the forces acting on the sides of each slice are neglected. The general calculation scheme used is presented in Fig. 9.

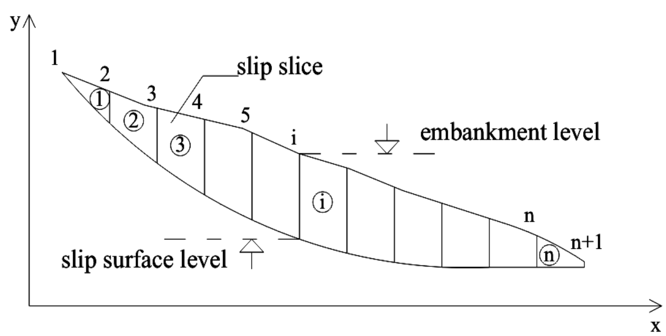


Fig. 9. General calculation scheme used by STAB-1 (after Athanasiu et al., 1983).

Therefore, the horizontal force resulting from the equilibrium condition for each individual slice is:

$$E_i = \frac{1}{2}\sum_{1}^{n} G_i \sin 2\alpha_i - tg\phi \sum_{1}^{n} G_i \cos^2 \alpha_i - c\sum_{1}^{n} \Delta l_i \cos \alpha_i \qquad (5)$$

, where: Gi = weight of "i" slice
α_i = angle between "i" slice base and horizontal axis
Δl_i = length of "i" slice base
tgϕ, c = shear strength parameters along the failure area
E_i = horizontal force for each slice

Shear strength parameters required in order to maintain the sliding soil mass into limit equilibrium result by imposing a zero value of E_i.Input data for the program consist of elevation values for points corresponding to the slices on the embankment surface, on the failure surface and on the water table level. The program determines the factor of safety, the limit axis' cutting points and also the cutting points for when there is installed a buttress of 100 kN/m at the base of the slope. The general calculation scheme is presented in Fig. 10.

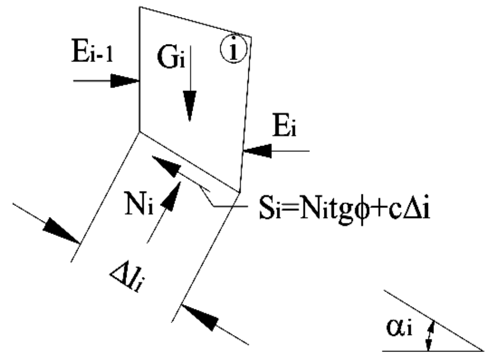


Fig. 10. General calculation scheme for STAB-1 (after Athanasiu et al., 1983).

The FOS is calculated by using the limit axis defined in Fig. 11.

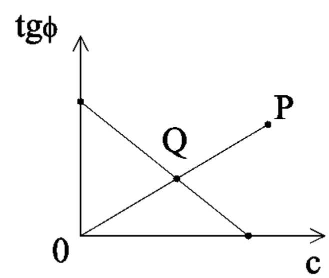


Fig. 11. Shear parameters envelope for limit equilibrium (after Athanasiu et al., 1983).

$$F_S = \frac{\overline{OP}}{\overline{OQ}} \qquad (6)$$

Equation 6 is obtained as follows: each pair of tgϕ and c values generates a point marked as Q on the axis, which ensures the limit equilibrium state of the slope; the point marked with P is generated by the intersection of the real shear strength parameters’ values of the analyzed soil. The values resulted by using STAB are presented in Table 3.

Table 3. FOS values with STAB method for initial and final

stage

Shear strength properties	Initial stage	Final stage
	FOS	
c=2.5kPa		
tgϕ = 0.1	0.609	1.05
tgϕ = 0.2	0.777	1.21
tgϕ = 0.26	0.877	1.31
tgϕ = 0.3	0.945	1.62
c=5kPa		
tgϕ = 0.1	0.961	1.46
tgϕ = 0.2	1.41	1.92
tgϕ = 0.26	1.69	2.19
tgϕ= 0.3	1.87	2.38

The differences between FOS values obtained by the two different methods of calculation are in strong connection with the hypothesis considered for the inter-slice forces.

CONCLUSIONS

Structure stability analysis is a major concern in engineering. A stability evaluation calculus is necessary for both new constructions, as well as for older ones, that have not benefited from the existence of computer programs for ease of calculation.

From the numerical modeling of the seepage and sliding phenomena occurring within the dike structure, results showed that the presence of a drainage system containing a geotextile as filter is necessary in order to increase the FOS values. However, a selection process is in order for a good efficiency of the remedial measure to be taken in such situations. The drainage material's presence was considered to be a very good option for increasing the FOS values, as shown in both numerical and mathematical analysis.

The geosynthetic material improves the overall stability of the dike in two ways, namely:

- by ensuring drainage through the structure and implicitly by increasing the shear strength parameters values (c = 2.5kPa, tgϕ = 0.3);
- by a favorable alteration of the failure surface, which leads to decreasing values of the active forces responsible for sliding $\left(\frac{1}{2}\Sigma G_i \sin 2\alpha\right)$.

The geotextile's presence also leads to a variation in humidity within the ash dike. The humidity value for saturated ash is equal to 68%, as determined by Eq. 7.

$$\omega_{sat} = \frac{n \cdot \gamma_w}{\gamma_s (1-n)} \tag{7}$$

On the other hand, according to the graph from Fig. 12, the shear strength parameters ϕ and c vary depending on humidity values. A variation of over 50% is observed for cohesion values and a three times higher value of the friction angle is registered.

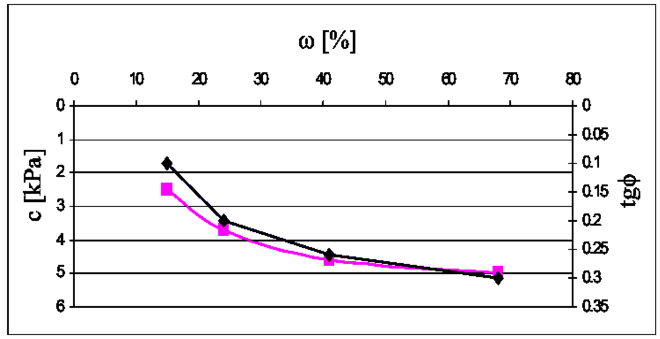


Fig. 12. Ash humidity versus shear strength parameters.

Direct shearing tests were performed on samples of ash at different humidity. In relation to the humidity range, shear strength parameters were determined according to Coulomb law. Similar to soils behavior, the studied ash emphasizes the connection between shear parameters ϕ and c, and humidity, due to the adhesion phenomenon taking place between solid particles within its structure.

In terms of stability, it is highly recommended for fly ash dikes to be subjected to stability loss analysis immediately after the hydraulic discharge of ash takes place, when the shear strength values are low. Therefore, the use of a geotextile filter is very useful in this stage, as it provides a humidity decrease within the dike.

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