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STABILITY ANALYSIS OF THE IMPOUNDMENT OF ASH

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ABSTRACT

An impoundment is an engineering construction used for the safe deposition of unexploitable waste from industrial and mining facilities. In terms of the legislative requirements of the Slovak Republic, a "Measurements Project" must be developed for each impoundment. In this document the prerequisites for the safe operation of an impoundment, the limit and critical values of the monitored phenomena and the facts influencing the safety of the impoundment and the area endangered by such a site are also defined. The safety and stability of an impoundment are verified according to a "Measurements Project" by considering stability at regular time intervals. This contribution presents, in the form of a parametric study, a stability analysis of an ash impoundment. The stability analysis provides an example of the utilization of an information database of the results of the regular monitoring of the geotechnical properties of the materials forming the impoundment´s body and the surrounding rock mass. The stability of the impoundment is expressed for a recent state – without a continuous water level in its body and, at the same time, for a hypothetical limit and critical water level according to the valid "Handling Regulations".

KEY WORDS

- *Ash impoundment,*
- *sedimented ash,*
- *shear strength,*
- *safety factor,*
- *slip surface,*
- *limit water level,*
- *critical water level,*
- *horizontal acceleration factor.*

1. INTRODUCTION

From a design and material point of view, impoundment is a markedly non-homogeneous engineering construction. The reasons for such non-homogeneousness are diverse. The dam system of an impoundment may be built from other geomaterials such as sediment in the accumulation area of the impoundment. In the course of its operation, changes in the technology of the building of an impoundment occur (change the hydraulic filling to transport by freight cars). The non-homogeneousness in the sedimented geomaterials is also influenced by their deposition and gradual sedimentation. We can also speak about non-homogeneousness from the point of view of the genetic divergence of the anthropogenic sediments and natural rock mass in which the impoundment is situated. A stability analysis of an impoundment is a demanding engineering task. The credibility of the results, when considering the stability of an impoundment, is conditioned by the aptness of the computing model of the impoundment, which actually describes not only the constructional arrangement, but also the properties of the geomaterials of the construction of an impoundment and the surrounding rock mass. The results of the regular and systematic monitoring of the geomaterials of an impoundment are the decisive pieces of information for the creation of a computer model that takes into account the constructional and material composition of the impoundment.

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2. DESCRIPTION OF THE ANALYZED IMPOUNDMENT

A method of stability analysis that utilizes the results of the monitoring of the properties of the geomaterials is presented as a stability consideration of an ash impoundment at Zemianske Kostoľany (”Definitive impoundment”). The aerial view of the impoundment is in Fig. 1.

The impoundment is of a valley type with a basic dam built of compacted ash with a gravel draining system. On the air side of the dam there is a backfill from the local werfen shale on a slope of 1:3. The basic dam is ~20.0 m high (the toe is at an elevation point of approx. 240.00 m above the sea level, and the crest is at an elevation point of approx. 260.00 m above the sea level). The elevation dams have a height of 3.00 to 5. 00 m. The basic dam and the elevation dams are built of deposited or brought-in ashes with a drainage system made from gravel drains.

Fig. 1 *The aerial view of the impoundment.*

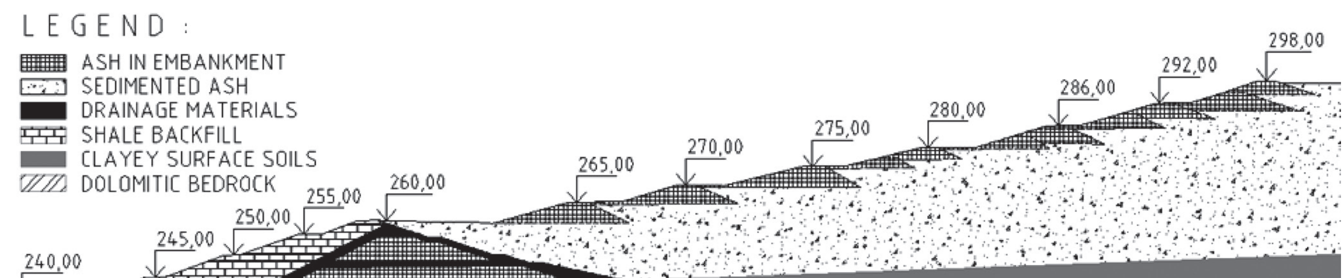

Fig. 2 *Schematic valley profile of the impoundment.*

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Fig. 3 *A view of the dam system of the impoundment.*

A schematic valley profile of the impoundment with the position of all the construction elements is in Fig. 2. A view of the dam system of the impoundment is in Fig. 3.

The impoundment has been in operation since 1985. Up to an elevation of 286.00 m above sea level, it is being deposited by an ”against the water“ method. From this level, the ashes are alternately deposited to the impoundment into two sealed meanders, wherefrom, after its sedimentation and the draining away of water, it is quarried and brought into the impoundment. By a modification of the technology of the deposition, the seepage of the water by the impoundment body was eliminated; the stability of the dam system was increased; and the losses of the transported water were reduced.

The subsoil of the impoundment consists of fine-grained soils, i.e, sandy and gravelly soils, under which there are dolomitic bedrocks in diverse stages of disintegration (of a gravelly and sandy nature). The soils, which by their occurrence in the subsoil significantly affect the stability relations of the impoundment, represent the contact of the impoundment body with the subsoil. These are fine-grained soils – clay and silty soils of CS-CL-CI-CH and MS-ML-MI-MH types. Under those soils there are sandy and gravelly soils (disintegrated dolomitic rocks), which have significantly better mechanical properties than the fine-grained soils. The recent working altitude is at an elevation point of 295.00 above sea level. The stability analysis of the impoundment verified the elevation of the dam system to an elevation point of 298.00 m above sea level.

3. DEFINING THE PROCEDURE AND INPUT PARAMETERS OF THE STABILITY ANALYSIS OF THE IMPOUNDMENT

For a stability analysis of an impoundment, the most unfavorable valley profile was chosen [3], [4], [7], [10]. In the calculations by the GEO 5.14 software [14], the Petterson [13] and Bishop [12] slice methods for circular slip surfaces and the Sarma [11] method for polygonal slip surfaces were applied. The stability analysis of the entire impoundment is performed per partes – the foot of the dam system, the centre of the dam system with a new elevation, and the entire dam system. For the most unfavorable valley profile of the impoundment and its individual parts defined, a set of cylindrical and polygonal slip surfaces was optimized, the most unfavorable of which (critical slip surfaces) are depicted in the profile of the impoundment in Figs. 4a, b.

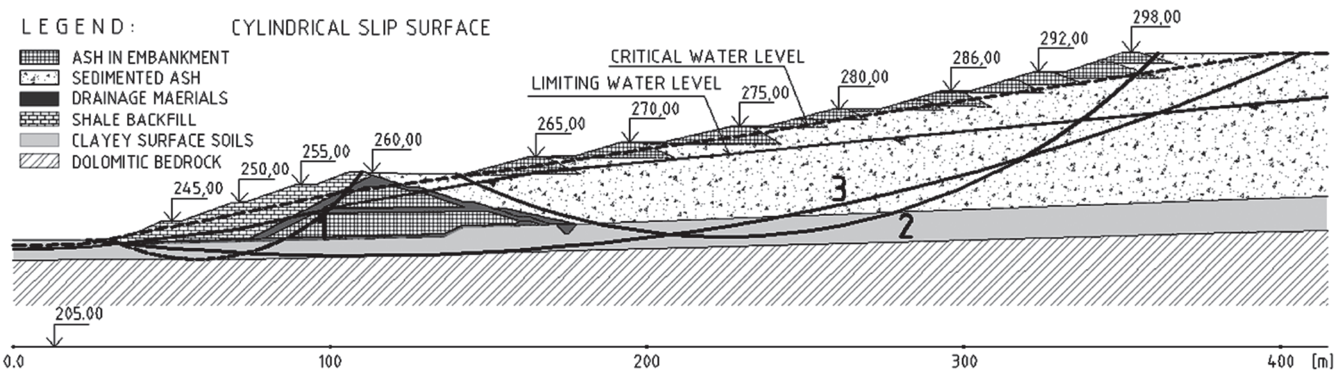

Fig. 4a *Valley profile of the impoundment – the critical circular slip surfaces.*

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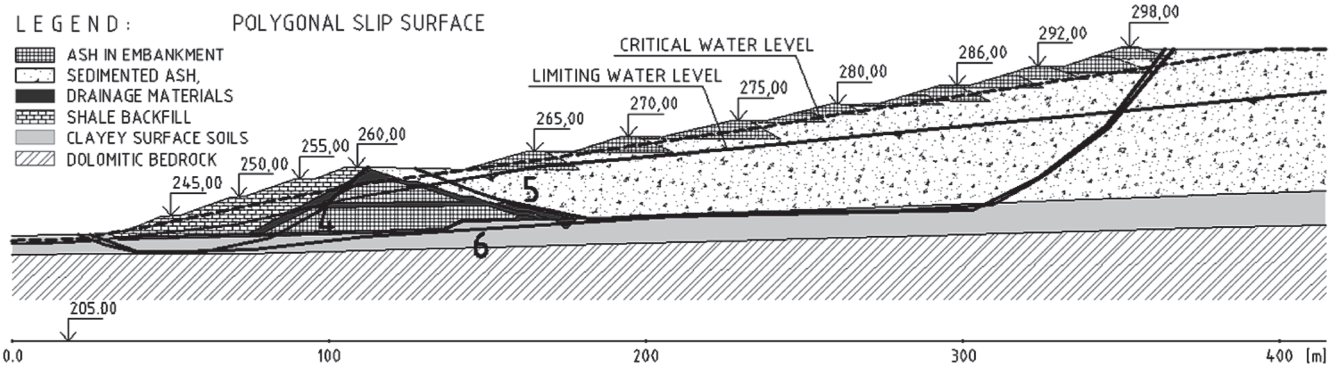

Fig. 4b *Valley profile of the impoundment – the critical polygonal slip surfaces.*

The characteristics of the properties of the geomaterials of the impoundment are alternatively taken into account in the calculations as the average and minimum ones. The decisive characteristics for the stability of the impoundment being considered are the parameters of the shear strength of the deposited ashes, the ashes in the dam system, and the clayey soils at the contact of the impoundment body with the subsoil. The minimum and average values of the parameters of the shear strength of the sedimented ashes and soils of the subsoil are specified from the results of the direct shear tests evaluated from the regular monitoring stages performed during 2000 – 2011 [1], [2], [5], [6], [8], [9], [10]. The average parameters are expressed from the average line of strength by statistical processing of all the measured data (solid line); the minimum parameters are expressed from the wrapper line of the strength of the minimum values of the measured data (dotted line), Figs. 5a, b. 492 test samples of the sedimented ashes and 32 test samples of the fine-grained soils forming the immediate subsoil of the impoundment, taken up during regular exploration stages, are incorporated into the statistical processing. The minimum value of the parameters of the shear strength of the ashes deposited in the dam system is considered as a historic minimum, which has been expressed for the dam ashes. The average parameters of the shear strength of the ashes of the dam system are introduced into the calculations in such a dimension as that of the sedimented ashes. The cohesion of the ashes is, according to their nature (non-cohesive geomaterials), ignored in the stability calculations. The parameters of the shear strength of the shale backfill of the air side of the basic dam and the gravel draining elements are expressed at the level of an expert estimation, taking into account their nature, method of incorporation, and grain composition. The minimum value of the dolomitic bedrock (dolomitic sands) forming the subsoil of the impoundment under the clay layer was defined by the minimum archive values of its shear strength.

The average parameters of the dolomitic bedrock are expressed at the level of an expert estimation, taking into account their grain composition. To summarize, all the parameters of the geomaterials considered in the stability analysis are expressed in Tab.1.

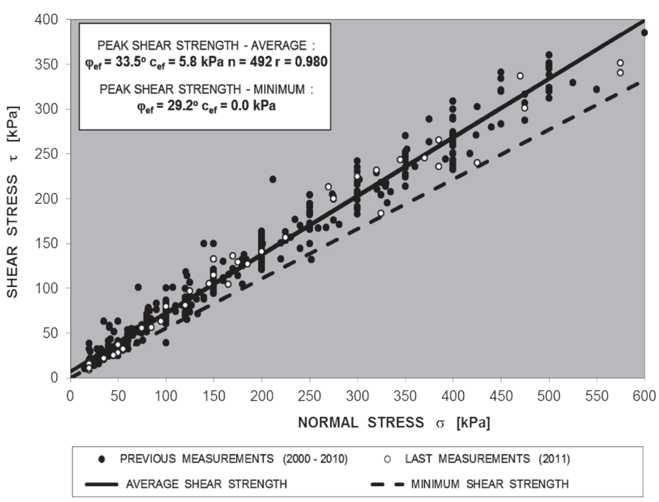

Fig. 5a *Expression of the average and minimum parameters of the shear strength of the deposited ashes.*

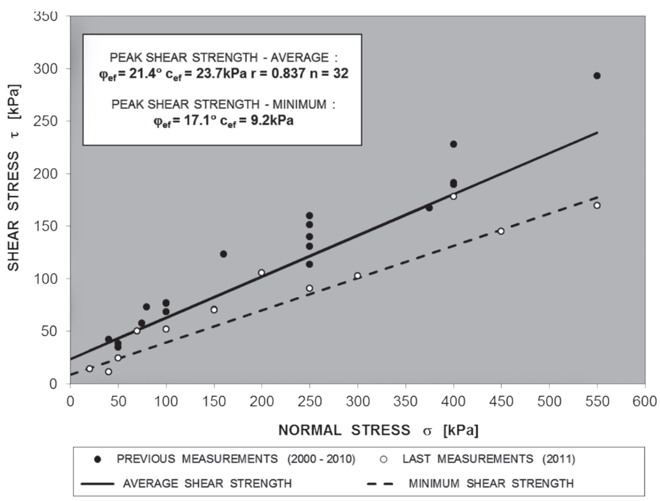

Fig. 5b *Expression of the average and minimum parameters of the shear strength of the subsoil soils.*

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Tab. 1 *Minimum and average parameters of the geomaterials considered in the stability analysis.*

LAYER	PARAMETERS					
	γ_n [kN.m^{-3}]	γ_{sat} [kN.m^{-3}]	MINIMUM PARAMETERS		AVERAGE PARAMETERS	
			φ_{ef} [°]	c_{ef} [kPa]	φ_{ef} [°]	c_{ef} [kPa]
ASH IN EMBANKMENT	12.2	14.5	25.0	0.0	33.0	0.0
SEDIMENTED ASH	12.0	14.0	29.0	0.0	33.0	0.0
SHALE BACKFILL	20.0	22.0	30.0	0.0	30.0	0.0
DRAINAGE MATERIALS	20.0	22.5	33.0	0.0	33.0	0.0
CLAYEY SURFACE SOILS	19.0	21.0	17.0	9.0	21.0	23.0
DOLOMITIC BEDROCK – SAND	19.0	20.7	24.0	0.0	35.0	0.0

Since 1998, as a consequence of the modification of the technology of the deposition of the hydro-mixture (only into the accumulation areas of the sealed meanders), the water level in the dam body of the impoundment has significantly declined. At present, the water level is found at the impoundment´s subsoil; this is also documented by the exploratory works of recent years and monitoring performed in compliance with the legislation by the impoundment administrator. The level of the groundwater in the subsoil oscillates approximately at the level of the initial situation prior to the deposition of the ashes in the valley. Therefore, in the first step of the stability analysis, the recent actual state of the impoundment´s stability is assessed – without the influence of the water level in the impoundment body. The valid “Handling Regulation” and the “Measurements Project ” define the limit and critical water levels, due to the possible critical condition of the sealed meanders. For this reason, the stability assessment also considers these hypothetical water levels.

In the stability analysis of the impoundment, the influence of the seismic load corresponding to the normative seismic load of the given locality is also considered. According to the map of the areas of seismic load on the territory of Slovakia, the region of the impoundment belongs to an area of seismic acceleration with a value of a_{gR} = 0.63 m.s^{-2}. Upon consideration of the stability of the ground slopes by means of so-called simplified pseudo-static methods, the seismic effects are introduced into the calculations by using a so-called factor of horizontal acceleration $K_h = a/g$, where a is seismic acceleration, and g is the acceleration of gravity 9.807 m.s^{-2}. The seismic effects are accepted in the calculations by means of the factor of horizontal acceleration $K_h = 0.07$.

4. RESULTS OF THE STABILITY ANALYSIS OF THE IMPOUNDMENT

According to Eurocode 7 [15], it should be verified that limit states are not exceeded. In a stability analysis of an impoundment, that is the failure of the dam slope´s system. When considering the limit state of the rupture of a structural element or section of soil, it should be verified that the design value of the corresponding resistance is more than the design value of the effects of all the actions. The current Slovak standard for impoundment [16] requires the expression of the stability of an impoundment through a safety factor. In addition, the stability analysis is developed in the form of a parametric study. The parameters are the properties of the geomaterials and water levels in the dam body of the impoundment. In the case of a parametric study, the safety factors illustratively give an idea of an impoundment´s stability. These are the reasons why the results of a stability analysis are expressed as safety factors.

Tab. 2a *Safety factors – impoundment without any consideration of the water level.*

SLIP SURFACE No.	SAFETY FACTOR – F_S WITHOUT WATER LEVEL	
	MINIMUM PARAMETERS	AVERAGE PARAMETERS
1	1.60 / 1.79	2.03 / 2.25
2	2.73 / 2.99	3.41 / 3.73
3	3.03 / 3.08	3.84 / 3.91
4	1.75	2.21
5	2.85	3.59
6	2.55	3.35
1*	1.25 / 1.40	1.59 / 1.77
2*	1.90 / 2.08	2.37 / 2.60
3*	1.99 / 2.02	2.52 / 2.56
4*	1.35	1.73
5*	2.00	2.52
6*	1.75	2.30

LEGEND :
Petterson / Bishop method for circular slip surfaces No. 1, 2, 3
Sarma method for polygonal slip surfaces No. 4, 5, 6
* - seismic load - factor of horizontal acceleration K_h = 0.07

Required safety:

$F_{S,min} > 1.0$	$F_{S,min} > 1.1$
$F_{S,min} > 1.3$	$F_{S,min} > 1.5$

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Tab. 2b *Safety factors – impoundment with consideration of limit water level.*

SLIP SURFACE No.	SAFETY FACTOR - F_S LIMITING WATER LEVEL	
	MINIMUM PARAMETERS	AVERAGE PARAMETERS
1	1.31 / 1.47	1.68 / 1.87
2	1.59 / 1.74	2.02 / 2.21
3	1.93 / 1.95	2.49 / 2.52
4	1.45	1.87
5	1.66	2.15
6	1.57	2.13
1*	1.01 / 1.13	1.30 / 1.45
2*	1.08 / 1.18	1.38 / 1.50
3*	1.25 / 1.26	1.62 / 1.64
4*	1.12	1.45
5*	1.14	1.47
6*	1.03	1.41

LEGEND :
Petterson / Bishop method for circular slip surfaces No. 1, 2, 3
Sarma method for polygonal slip surfaces No. 4, 5, 6
* - seismic load - factor of horizontal acceleration K_h = 0.07

Required safety:

$F_{S,min} > 1.0$	$F_{S,min} > 1.1$
$F_{S,min} > 1.3$	$F_{S,min} > 1.5$

Tab. 2c *Safety factors – impoundment with consideration of critical water level.*

SLIP SURFACE No.	SAFETY FACTOR - F_S CRITICAL WATER LEVEL	
	MINIMUM PARAMETERS	AVERAGE PARAMETERS
1	1.10 / 1.22	1.42 / 1.58
2	1.10 / 1.21	1.43 / 1.57
3	1.35 / 1.38	1.79 / 1.83
4	1.21	1.59
5	1.13	1.49
6	1.13	1.58

LEGEND :
Petterson / Bishop method for circular slip surfaces No. 1, 2, 3
Sarma method for polygonal slip surfaces No. 4, 5, 6

Required safety :

$F_{S,min} > 1.0$	$F_{S,min} > 1.3$

The resulting critical slip surfaces (Nos.1 to 6), selected from the overall computing set of the surfaces (after optimization of the calculations) for the most unfavorable profile of the impoundment dam system examined are presented in Figs. 4a, b. The respective safety factors for the critical circular slip surfaces in Fig. 4a and for the critical polygonal slip surfaces in Fig. 4b are presented in Tab. 2a for the recent state without the presence of a continuous water level, in Tab. 2b for the limit water level, and in Tab. 2c. for the critical water level in the impoundment body.

The evaluation of the results of the stability analysis documents that the safety factors without consideration of the water level are within the interval of F_S ⟨1.60 ; 3.08⟩ for the alternative with the minimum parameters of the shear strength of the geomaterials (required safety $F_{S,min}$ > 1.30) and F_S ⟨2.03 ; 3.91⟩ for the alternative with the average parameters of the shear strength of the geomaterials (required safety $F_{S,min}$ > 1.50). The safety factors for the limit water level are for the alternative with the minimum parameters of the shear strength of the geomaterials within the interval F_S ⟨1.31 ; 1.95⟩ (required safety $F_{S,min}$ > 1.30) and for the alternative with the average parameters of the shear strength of the geomaterials F_S ⟨1.68 ; 2.52⟩ (required safety $F_{S,min}$ > 1.50). If the water level in the impoundment body reaches a critical level, the safety factors for the alternative with the minimum strength parameters are within the interval F_S ⟨1.10 ; 1.38⟩ (required safety $F_{S,min}$ > 1.0) and for the average parameters of the shear strength of the geomaterials to the extent of F_S ⟨1.42 ; 1.83⟩ (required safety $F_{S,min}$ > 1.30).

At the same time, the safety requirements are fulfilled at the seismic load of $F_{S,min} \geq 1.0$ for the minimum parameters of the shear strength of the geomaterials, $F_{S,min} \geq 1.1$ for the average parameters of the shear strength of the geomaterials and the impoundment body without water, and for the limit water level in the impoundment body. The case that in the impoundment body at the critical water level a seismic load of the area by a standard design earthquake will occur at the same time is not realistic; therefore, it was not analyzed.

5. CONCLUSION

The safety of an impoundment is expressed on the basis of its stability analysis. Its feasibility is conditioned by the aptness of the computing model of the impoundment, which must realistically describe not only the constructional arrangement but also the properties of the geomaterials of the construction of the impoundment and the surrounding rock mass. The information database of the properties of the impoundment, expressed on the basis of the results of regular monitoring stages, is the basic input for the creation of a computing model, taking into account the construction and material composition of the impoundment. The stability consideration of the impoundment is, due to its non-homogeneousness, a demanding task. The expression of the stability of the impoundment by a single, definite value is therefore exacting. A more suitable method is represented by stability analyses of the impoundment in the form of parametric studies that utilize the results of the monitoring of

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properties of the impoundment geomaterials. The parameterization of the properties of the geomaterials forming the impoundment and surrounding rock mass enables the definition of the stability of the impoundment from the least favorable to the actual state.

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