

STABILITY ANALYSIS OF WASTE LANDFILLS ON POTENTIALLY UNSTABLE TERRITORY

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Abstract

The article presents the stability analysis of two adjacent waste landfills located in a potentially unstable territory. One of the waste landfills is reclaimed and consists of ash. Municipal solid waste is actively deposited in the second landfill. In the space between the landfills, the expansion of the municipal solid waste landfill is planned, with a partial overlap of the reclaimed ash landfill. The instability of the area where the landfills are located is due to its susceptibility to the formation of landslides. The article presents the results of experimental verifications of the peak shear strength parameters of the ashes and the peak and residual shear strength of the soils forming the subsoil of both landfills and serve as input for stability analyses. The shear strength parameters of municipal waste are defined on the basis of literature research. The potential instability of both waste landfill territories was taken into account using the parameters of the residual shear strength of the subsoil. The stability analysis of waste landfills is expressed using both the peak and residual shear strength parameters of the subsoil of waste landfills. In addition, the effect of seismic loading on both landfills is considered in the stability analysis.

Keywords:

Municipal solid waste;
Ash landfill;
Safety factor;
Residual shear strength;
Seismic loading.

1 Introduction

The paper deals with the stability of waste landfills in an area threatened by intensive landslide activity. The issue of the stability of waste dumps located in landslide areas is one of the important environmental aspects of the sustainable development of human society.

The territory of the Handlová basin is significantly affected by landslides [1, 2]. The Handlová basin belongs to the areas with the highest occurrences of slope movements in Slovakia. Forty eight percent of the total area is affected by slope deformations [3]. A catastrophic landslide in 1960 that moved 20 million cubic meters of sliding mass damaged 150 buildings, 2 km length road, water supply piping network and several parts of high-voltage power lines [4].

The stability of waste landfill directly affect the safety of people and property. The stability analysis of waste landfill slope is among the most significant engineering concerns in waste landfill operations. A number of studies have been conducted on the stability problem of waste landfills. There are numerous studies in the literature on the stability of slopes in waste landfills. In these studies, the slope stability analyses were carried out using LEM (limit equilibrium method) and FEM (finite element method). The slope failure at a waste landfill in California was analyzed carried out using LEM (limit equilibrium method) [5]. The stability analysis of waste landfill slopes in [6] was according to the results obtained from laboratory tests, field experiments, and back-calculations. Ten landfill failures were discussed in [7]. According numerical analyses for stability calculations depend more on shear strength than other parameters. The slope stability analyses at two existing solid waste landfills in Brazil were discussed in [8]. As a result of the study, it was stated that the determination of suitable shear strength parameters of waste are very important in the analysis. The three-dimensional numerical analyses to model the slope failure occurring in the Kettleman Hills Landfill are presented in [9]. The study showed that the internal friction angle and cohesion values obtained as a result of the back-analysis carried out for the post-failure slope and the values obtained by the laboratory experiments were compatible. The

shear strength of waste landfills was analyzed by back-analysis of failed waste slopes using laboratory tests and field experiments in [10]. The stability of waste landfill slopes as a function of time and decomposition was analyzed in [11]. In the study, analyses were carried out using LEM (limit equilibrium method) and FEM (finite element method). The shear strength parameters of waste landfills were investigated using back-analysis of failed waste slopes in [12]. The back analyses of the failed waste slopes in four landfills was presented. Each of the landfill slope failures was reviewed, and the results of the back-analyses were presented. At the end of the study [12], the obtained and recommended parameters were compared with other studies.

The analyzed waste landfills are located approximately 1.2 km west of the town of Handlová. One of the landfills has been actively used for the storage of municipal solid waste since 1996. The thickness of the municipal waste landfill is up to 25 m. In the immediate vicinity of the municipal solid waste landfill there is a reclaimed power plant ash landfill, which was in operation in 1957-1998. Reclamation of the ash landfill consisted of adjusting the slopes to a slope of 1:3, covering them with 1.5 mm HDPE foil on which a drainage geocomposite layer was placed. The surface of the ash landfill was covered with a 0.5 m clay reclamation layer. The thickness of the ash landfill is up to 30 m. The situation of both landfills is presented in Fig.1 [13].

The mutual location of both landfills created a space between the landfills, which the current operator of the active municipal waste landfill decided to use to expand the landfill and use this space for the storage of municipal waste. A view of the space between the landfills and the planned waste landfill is shown in Fig. 2 [14]. The profile of both landfills (A-A') with the proposed filling of the space between the landfills is presented in Fig. 3 [15].

2 Input data and methods

2.1 Properties of subsoil and landfill material

Fig. 4 shows a part of the slope stability map in the vicinity of the town of Handlová with the location of waste landfills [16]. It is clear from Fig. 4 that the location of the waste landfills is located in a potentially unstable territory. In the immediate vicinity of landfills, unstable territory is indicated from the point of view of slope deformations.

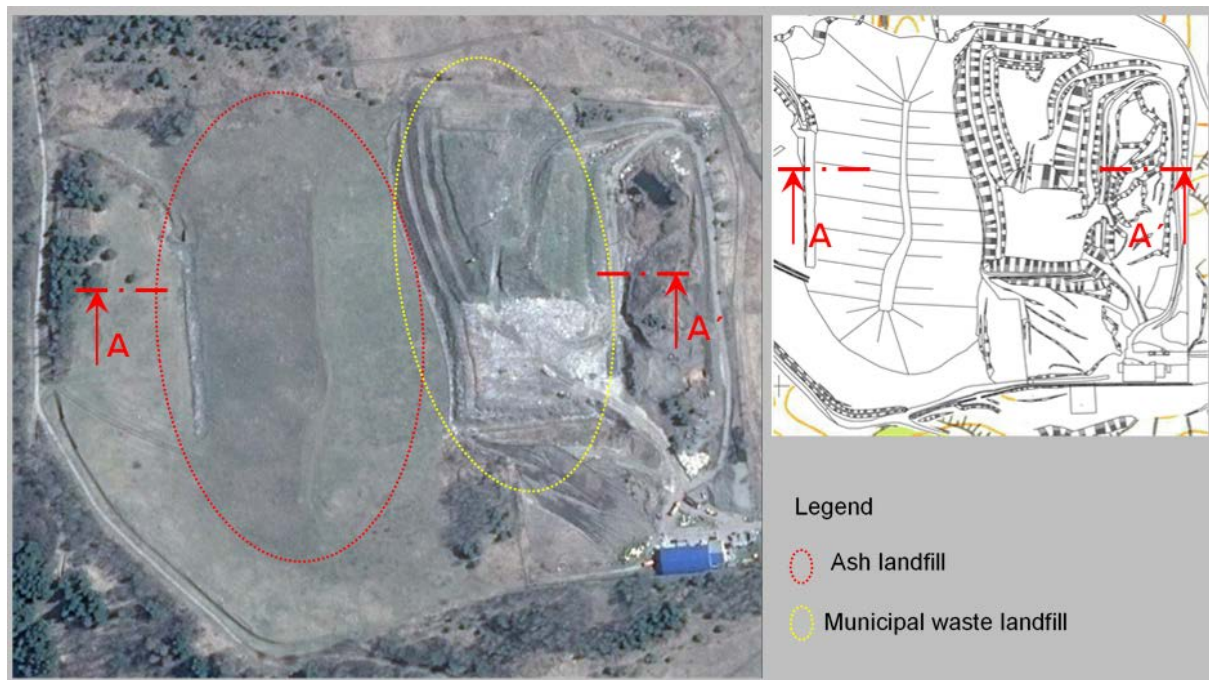


Fig. 1: The overall situation of both landfills [13].



Fig. 2: View of the space between the municipal waste landfill and the ash landfill [14].

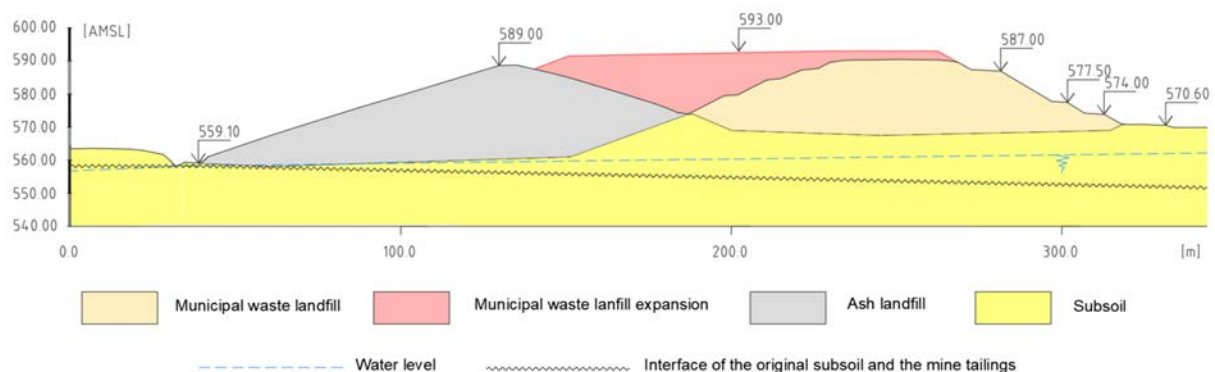


Fig. 3: Cross-section of the landfills A-A' [15].

In addition to the fact that the waste landfills are located in a potentially unstable area from the point of view of landslides, the territory was used in the past before the construction of both dumps for the storage of mine tailings from the local mine. The thickness of the mine tailings in the original subsoil under the waste landfills is variable and varies from 1.0 m to 21.5 m. The position of the interface between the original subsoil and the mining tailings is marked in the profile of both landfills in Fig.3. For these reasons, during the survey work carried out at the site of the waste landfills, a significant emphasis was placed on defining the properties of the soils located in the subsoil of both waste landfills.

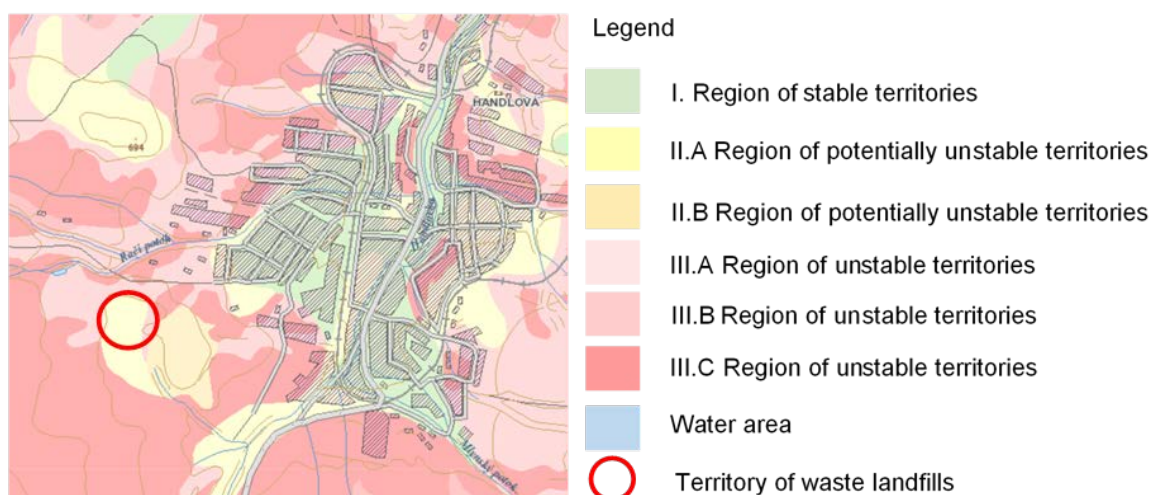


Fig. 4: Atlas map of slope stability of the Slovak Republic – Handlová territory [16].

Experimental measurements of the properties of the soils that form the subsoil of waste landfills were aimed at defining and comparing the properties of the mine tailings that form the immediate subsoil and the soils that form the original subsoil of waste landfills. As part of the exploration work, 12 samples were taken from mine tailings and 12 samples from soil of the original subsoil of the waste landfills. A mutual comparison of the properties of mine tailings and soils in the original subsoil of waste landfills

showed that they are practically identical soils. This is evidenced not only by the mutual comparison of the ranges of grain size distribution in Fig. 5, but also by the position of the soil samples taken in Casagrande's plasticity diagram in Fig. 6 and the mutual comparison of index properties in Tab. 1.

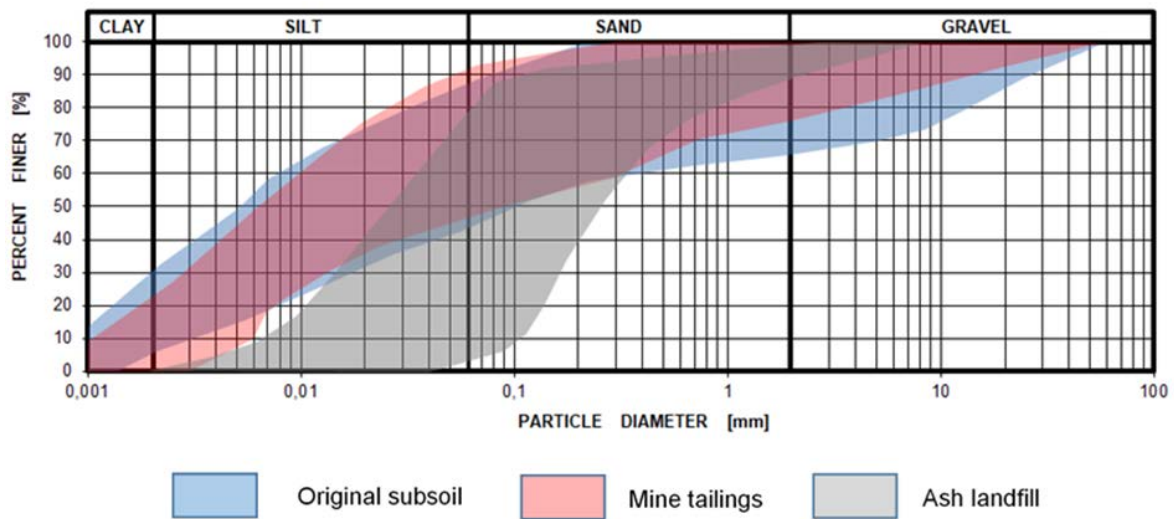


Fig. 5: Range of the grain size distribution of the original subsoil, mine tailings and ash landfill [15].

Based on a comparison of the properties of soils taken from the original subsoil and from the mine tailings under the waste landfills, the subsoil of the landfills can be characterized as one complex in which high to very high plastic clays and silts predominate (CH/CV/MH/MV), to a lesser extent clays and sandy silts (CS/MS) and occasionally gravelly clays (CG).

Due to the potential instability of the territory in terms of landslides and the presence of clayey and silty soils highly plastic to very highly plastic in the subsoil of waste landfills, attention was focused on determining the peak and residual shear strength of the soils. Shear strength parameters were determined by direct shear tests of CD type on samples of dimensions 60/60/25 mm. In the first phase of the test, the soil samples were reconsolidated by geostatic stress acting at the depth of sampling. Subsequently, a shear test was carried out to determine peak shear strength parameters (ϕ_{ef} ; c_{ef}) at the direct shear test speed of $0.002 \text{ mm} \cdot \text{min}^{-1}$. After determining the peak strength was determined, the samples were subjected to reverse displacement until the observed shear strength, and then the residual shear strength (ϕ_r ; c_r) were determined at the speed of the direct shear test $0.002 \text{ mm} \cdot \text{min}^{-1}$. The average peak and residual shear strength parameters expressed together for the samples taken from mine tailings and from the original subsoil of landfills are presented in Fig. 7. A view of the sliding surface of the tested soil samples after determining the residual shear strength is in Fig. 8.

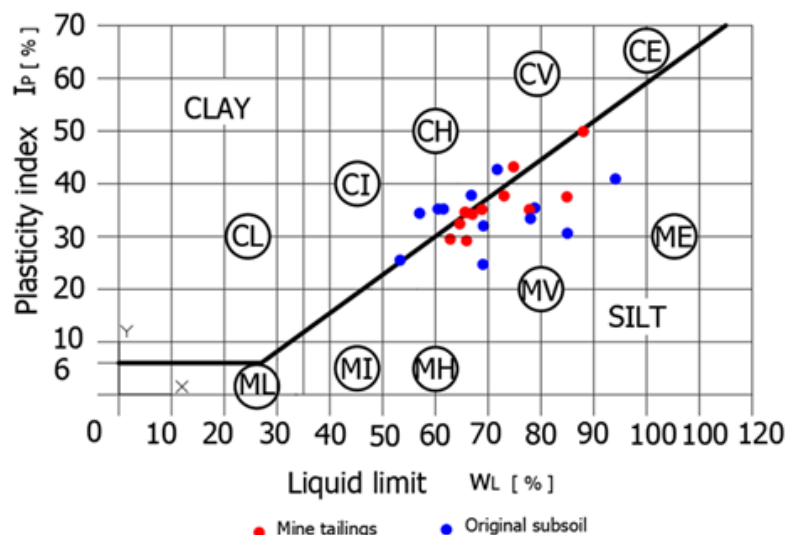


Fig. 6: Comparison of the original subsoil and mine tailings in Casagrande's plasticity graph [15].

Table 1: Properties of original subsoil and mine tailings [15].

Parameter	Original subsoil		Mine tailings	
	Average	Range of values	Average	Range of values
ρ_s [g.cm ⁻³]	2.67	(2.60 ; 2.71)	2.62	(2.54 ; 2.69)
n [%]	49.1	(38.4 ; 55.1)	49.4	(45.6 ; 61.1)
S_r [%]	98.5	(91.2 ; 100.0)	88.8	(78.6 ; 99.9)
w [%]	36.9	(21.9 ; 51.2)	36.5	(29.8 ; 67.4)
w_p [%]	36.4	(22.6 ; 54.4)	35.5	(31.0 ; 47.4)
w_L [%]	70.4	(53.3 ; 94.1)	71.6	(62.8 ; 84.9)
I_p [%]	34.0	(24.7 ; 42.7)	36.1	(29.2 ; 49.9)
I_c [-]	0.98	(0.77 ; 1.19)	0.99	(0.47 ; 1.27)

The range of grain size distribution of the samples taken from the ash landfill is presented in Fig. 5. Ashes can be characterized as silty sands (SM) and poorly grained sands (SP). In the past, the ash landfill was built as a landfill without regular compaction. The consolidation of the ashes was affected only by their weight. To determine the peak shear strength of the ashes (ϕ_{ef} ; c_{ef}), the samples were artificially prepared at a bulk density approximately corresponding to the bulk density of the ashes in the landfill. The speed of direct shear testing was 0.01 mm.min⁻¹. The average parameters of peak shear strength of the ashes are presented in Fig.7.

The granular composition and shear strength of the deposited municipal waste have not been experimentally verified. Estimation of unit weight and shear strength of municipal waste was based on experimental verifications of these properties and stability analyzes reported in [17-19]. The parameters used in the stability analysis of the slope of the waste dump in [17] were for the shear strength of the waste $\phi_{ef} = 18^\circ$; $c_{ef} = 5$ kPa and for the unit weight of the waste $\gamma_n = 8.0$ kN.m⁻³. Through experimental in situ tests, the authors [18] verified the value of the unit weight of the waste $\gamma_n = 11.5 - 12.6$ kN.m⁻³. The shear strength of the waste was verified in [18] with triaxial tests. The dependence of the change in the shear strength of municipal waste on the age of storage and axial deformation is for the friction angle in Fig. 9a and cohesion in Fig. 9b. Fig. 9a shows that the increase in the value of the friction angle of the waste depends on the increase in deformation and the age of storage, while this trend is opposite for the value of cohesion Fig. 9b. Similar conclusions are formulated for the shear strength of municipal waste on the basis of triaxial tests of municipal waste in [19] Fig.10 and this is also confirmed by the literature search Fig.11 in [19].

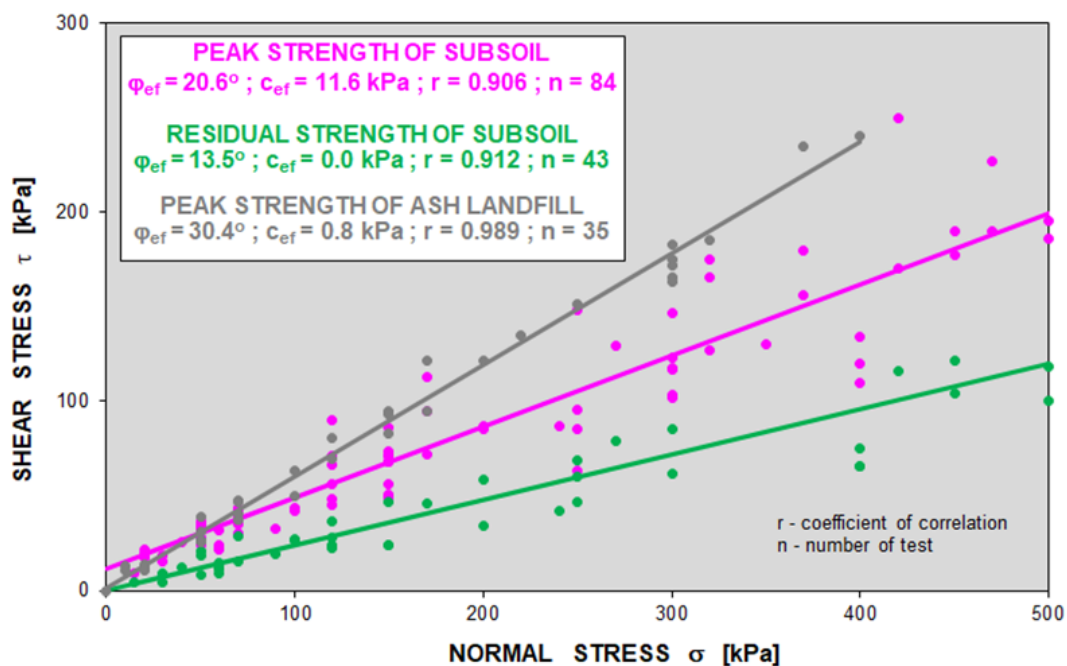


Fig. 7: Shear strength of the subsoil and ash landfill [15].

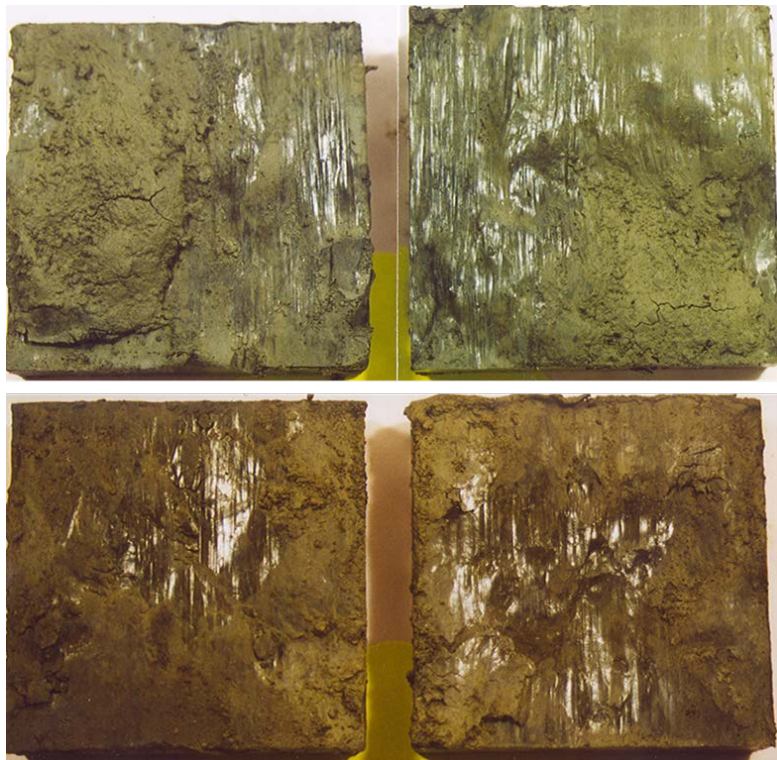


Fig. 8: View of the sliding surface of the subsoil samples after the determination of the residual strength [15].

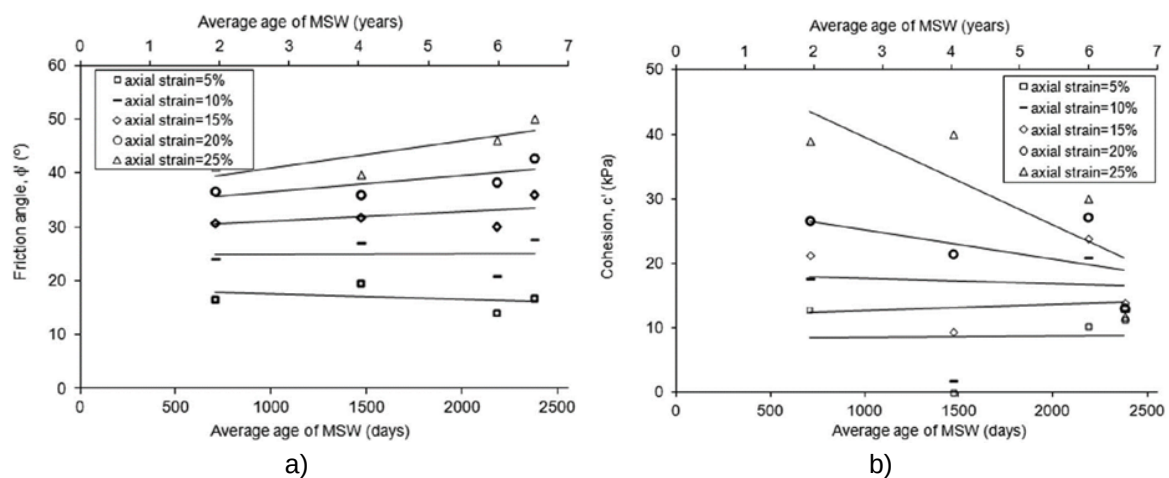


Fig. 9: Relationship between shear strength parameters (a, friction angle; b, cohesion) and age of MSW and axial strain [18].

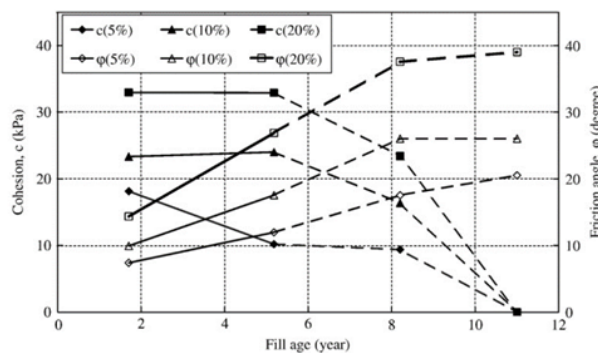


Fig. 10: Relationships of shear strength parameters at a range of strains to the fill age of MSW [19].

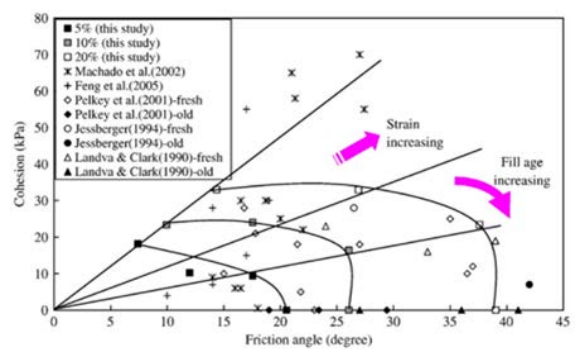


Fig. 11: Summary of the shear strength of MSW in the research literature [19].

The analyzed municipal solid waste landfill has been in operation for 28 years. The expansion of this landfill in Fig. 2 will extend up to the consolidated reclaimed ash landfill, whose deformations caused by municipal waste loading will be minimal. For these reasons and taking into account the parameters of the shear strength of solid municipal waste mentioned in [17-19], the parameters of municipal waste were considered in the stability analysis at the level of $\gamma_n = 11.0 \text{ kN.m}^{-3}$; $\varphi_{ef} = 25^\circ$; $c_{ef} = 5 \text{ kPa}$. The resulting parameters of all geomaterials considered in the stability analysis of waste landfills are summarized in Tab.2.

Table 2: Geomaterial parameters considered in stability analysis.

Geomaterial parameters	Municipal landfill	Municipal landfill expansion	Ash landfill	Subsoil
$\gamma_n \text{ [kN.m}^{-3}\text{]}$	11.0	11.0	12.0	19.0
$\gamma_{sat} \text{ [kN.m}^{-3}\text{]}$	12.5	12.5	13.5	19.5
$\varphi_{ef} / \varphi_r \text{ [}^\circ\text{]}$	25.0*	25.0*	30.0*	20.6* / 13.5**
$c_{ef} / c_r \text{ [kPa]}$	5.0*	5.0*	0.0*	11.6* / 0.0**

Notes: * peak shear strength parameters / ** residual shear strength parameters.

2.2 Methods of stability analysis

The stability analysis of waste landfills was carried out using analytical methods of limit equilibrium. Circular sliding surfaces were analyzed using calculation methods according to Bishop [20] and Spencer [21], and polygonal sliding surfaces using calculation methods according to Spencer [21] and Sarma [22]. The assumptions of the methods mentioned are also clearly stated in [23]. The software product GEO 5 (2023) [24] was used. The stability analysis of the waste landfills was carried out assuming the maximum level of the measured water level in the observation probes in the vicinity of the waste landfills. Seismic effects in waste landfills were assessed using the pseudostatic method, where the structure is loaded with static forces taking into account the effect of seismicity [25-26]. According to the map of seismic risk areas in Slovakia [26], the territory of waste landfills belongs to the seismic acceleration area with a value of $a_{gR} = 0.63 \text{ m.s}^{-2}$. Seismic effects were introduced into the calculations by the horizontal acceleration factor $K_h = 0.07$. The stability analysis of waste landfills was carried out in two alternatives:

- Alt. I. Use of peak shear strength parameters for the subsoil of waste landfills:
 - the slope of the ash landfill (circular sliding surfaces No. 1,2,3 / polygonal sliding surfaces No. 7,8,9),
 - the slope of the municipal waste landfill (circular sliding surfaces No. 4,5,6 / polygonal sliding surfaces No. 10,11,12) Fig.12.
- Alt. II. Use of residual shear strength parameters for the subsoil of waste landfills:
 - the slope of the ash landfill (circular sliding surface No. 1 / polygonal sliding surface No. 3),
 - the slope of the municipal waste landfill (circular sliding surface No. 2 / polygonal sliding surface No. 4) Fig.13.

An overview of the results of the stability analysis of waste landfills, as expressed in factors of safety (F_s) is presented in the Tab. 3 for Alternative I. and for Alternative II. in the Tab. 4.

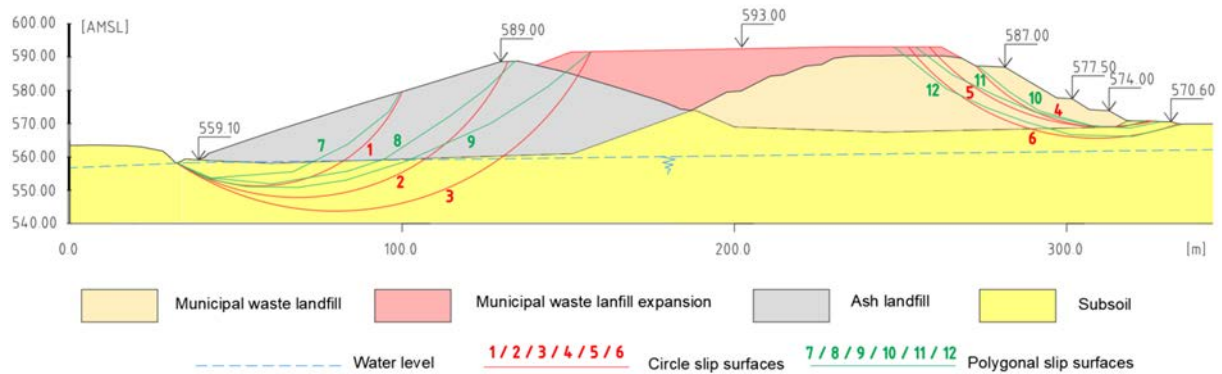


Fig. 12: Alternative I. - peak strength parameters of subsoil.

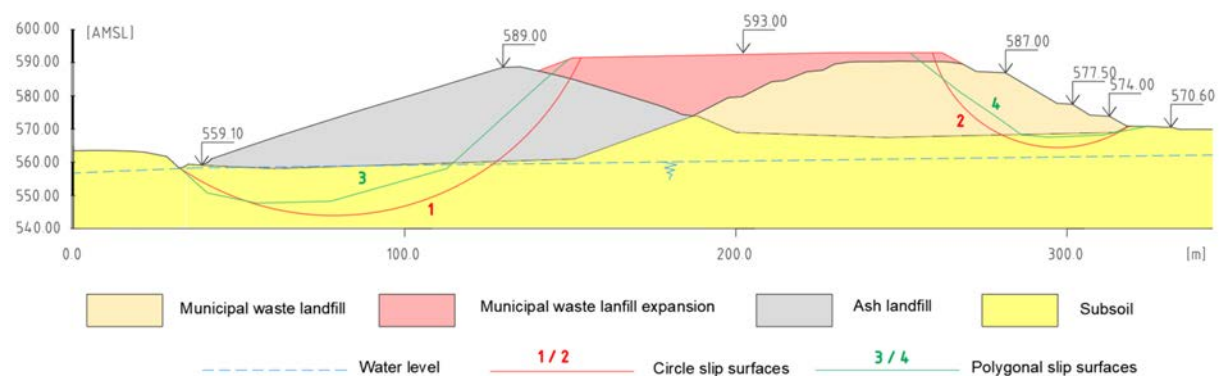


Fig. 13: Alternative II. – residual strength parameters of subsoil.

Table 3: Factors of safety F_s – peak strength parameters of subsoil.

Factors of safety F_s [-]					
Circle slip surface (Bishop / Spencer)			Polygonal slip surface (Sarma / Spencer)		
Slip surface No.	without seismicity	with seismicity	Slip surface No.	without seismicity	with seismicity
1	1.97 / 1.95	1.52 / 1.50	7	1.93 / 1.93	1.51 / 1.51
2	1.90 / 1.88	1.46 / 1.44	8	1.82 / 1.82	1.42 / 1.42
3	2.02 / 2.01	1.51 / 1.50	9	1.92 / 1.91	1.47 / 1.47
4	1.79 / 1.78	1.48 / 1.48	10	1.76 / 1.80	1.47 / 1.49
5	1.71 / 1.70	1.41 / 1.41	11	1.75 / 1.78	1.44 / 1.46
6	1.99 / 1.97	1.59 / 1.58	12	1.96 / 2.01	1.56 / 1.59

Note: Seismic load – factor of horizontal acceleration $K_h = 0.07$.Table 4: Factors of safety F_s – residual strength parameters of subsoil.

Factors of safety F_s [-]					
Circle slip surface (Bishop / Spencer)			Polygonal slip surface (Sarma / Spencer)		
Slip surface No.	without seismicity	with seismicity	Slip surface No.	without seismicity	with seismicity
1	1.29 / 1.27	0.95 / 0.94	3	1.27 / 1.26	0.96 / 0.95
2	1.39 / 1.35	1.12 / 1.09	4	1.26 / 1.26	1.03 / 1.02

Note: Seismic load – factor of horizontal acceleration $K_h = 0.07$.

3 Conclusion

The results of the presented stability analysis of waste landfills located in a potentially unstable territory show that the stability of both landfills will not be threatened by the proposed expansion of the municipal solid waste landfill if the seismic load is not taken into account:

- ✓ Ash landfill
 - considering peak parameters of the shear strength of the subsoil Factors of safety $F_s = \langle 1.82 ; 2.02 \rangle$,
 - considering residual parameters of the shear strength of the subsoil Factors of safety $F_s = \langle 1.26 ; 1.29 \rangle$,
- ✓ Municipal waste landfill
 - considering peak parameters of the shear strength of the subsoil Factors of safety $F_s = \langle 1.70 ; 2.01 \rangle$,
 - considering residual parameters of the shear strength of the subsoil Factors of safety $F_s = \langle 1.26 ; 1.39 \rangle$.

In the case of seismic loading after the shear strength of the subsoil has been exhausted, when sliding surfaces are formed and the shear strength of the soil in the subsoil of the waste landfills drops to the residual strength, the proposed expansion of the solid municipal waste dump will threaten the stability of both waste landfills:

- ✓ Ash landfill
 - considering peak parameters of the shear strength of the subsoil Factors of safety $F_s = \langle 1.42 ; 1.52 \rangle$,
 - considering residual parameters of the shear strength of the subsoil Factors of safety $F_s = \langle 0.94 ; 0.96 \rangle$,
- ✓ Municipal waste landfill
 - considering peak parameters of the shear strength of the subsoil Factors of safety $F_s = \langle 1.41 ; 1.59 \rangle$
 - considering residual parameters of the shear strength of the subsoil Factors of safety $F_s = \langle 1.02 ; 1.12 \rangle$.

Waste landfills are engineering structures, the shape and material parameters of which change over time and in space. They represent an environmental burden for both the present and the future; the solution to their issues must be gradual and systematic in order to reduce the possibility of accidents to a minimum. One of the evaluation criteria for the safety of waste landfills is the analysis of their stability. Assessing the stability of a waste landfill is a difficult task due to its non-homogeneity. The quality of a stability analysis is conditioned by the accuracy of the computational model of the waste landfill, which must not only realistically describe the structural arrangement, but also the properties of the geomaterials of the waste landfill and the surrounding rock massif. The properties of a waste landfill's geomaterials and subsoil of the waste landfill expressed on the basis of experimental verifications are the basic input for creating a computational model of a waste landfill. From this point of view, the authors of the article propose to focus future research mainly on the verification of the properties of geomaterials of waste landfills and the use of numerical methods for the stability analysis of landfill slopes. Municipal waste properties could be verified in a model municipal waste landfill using a combination of laboratory experimental measurements and cone penetration tests CPT [27]. After verifying the properties of the geomaterials of the waste landfills by laboratory and penetration tests, it would be appropriate to verify the stability analysis of the slopes of the waste landfills by comparing the results of the limit equilibrium methods (LEM) and numerical methods (FEM or Meshfree – MLPG) [28].

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