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STABILITY OF STORED MUNICIPAL WASTE FOR DIFFERENT SEALING SYSTEMS

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Abstract
The paper presents analyses of the municipal waste stability, stored in a landfill with the specific parameters of the waste massif, such as height, width and slope inclination. The massif of waste is lined by a simple drainage/sealing layer, consisting of a sand layer, non-woven geotextile, HDPE double-textured geomembrane and two different sealing mineral layers. The structure stability analysis was performed using a numerical program, relating to the methods: Fellenius/Petterson, Bishop, Spencer, Janbu and Morgenstern-Price. The considerations were carried out according to approach 3 (DA3) for the ultimate limit state GEO of Eurocode 7. The values of the utilization factor and the factor of safety were compared. Municipal waste is generally stable if the slope of the waste is ≤ 25°. With a slope inclination of 30°, the structures of waste massifs are stable up to a height of 10 m. Using the Fellenius/Petterson method can lead to an underestimation of the factor of safety and an overstatement of the degree of utilization; other methods give comparable results. Changing the material of the mineral sealing layer leads to a change in the course of the circular slip line.

Keywords: **Analysis of stability; Storage of municipal waste; Sealing layers of landfills; Waste stability calculations.**

1. INTRODUCTION

Sealing the base and slopes of the landfill creates an impermeable sealing barrier, protecting the ground against the penetration of leachates and landfill gases into the lower layers of the ground and groundwater, as well as draining the resulting leachate to the treatment system. High-density polyethylene (HDPE) geomembranes are one of the synthetic materials used as artificial sealing barriers in municipal waste landfills. One of the disadvantages of HDPE geomembrane is its smooth surface, which results in a low value of interface shear strength obtained for multilayered liner systems. This fact was especially noticed after the slope-stability failure of a Class I hazardous waste landfill at Kettleman Hills in California [12, 16]. The failure was caused by insufficient shear strength between layers of mixed storage seals. The interaction of smooth geomembrane and compacted clay layer was characterized by a very low residual value of the interface friction angle equalled 8°. Nowadays, geomembranes with textured surfaces are produced to prevent slippage along phases with mixed seal systems.

Factors that affect landfill stability can be divided into internal (geological) and external (geo-environmental). More detailed they can be assessed as [7]: engineering properties of waste, structural features of the waste body (leachate and landfill gas) and dynamic engineering geological processes (earthquake, rainfall, leachate, excavation, overloaded).

Important elements affecting the stability of the landfill are the geometric dimensions (height, width and inclination of the slope of the waste massif), as well as their physical and mechanical parameters. Municipal waste collected in landfills is a material that is very diverse in terms of morphology and density. Fresh municipal waste has a density in the range of 0.4–1.0 Mg/m^3, while landfill waste has a density of 0.8–1.2 Mg/m^3 [25]. The most common ranges of strength parameters are about 20–35° for the angle of internal friction and 15–40 kPa for the cohesion resistance [26]. The slightly different values of strength parameters are given by Dixon et al. [3]: 15–42° for the angle of internal friction and 0–28 kPa for cohesion intercept. The shear strength of municipal waste varies over time, which is mainly related to its compression and decomposition of organic substances. The period of about 1.5–3 years after the ending of deposition corresponds to a change in the intensity of the processes of bio-decomposition [6]. Attention should also be paid to the gradual decrease in the strength parameters of waste due to the progressing decomposition of municipal waste.

Many publications have been assigned to the issue of the stability of landfills, e.g. [2, 8–10, 13]. Both the limit equilibrium methods based on a cylindrical (circular) slip surface and the finite element method (FEM) can be used to analyze the stability of landfills. In the most used limit equilibrium methods, the factor of safety (F) determined from the ratio of the stabilizing resistances and the destabilizing effect of actions is to be greater than the permissible value of the stability factor, which in the case of landfills should be taken in the range of 1.2 to 1.3, depending on the importance of the facility and threats to the adjacent areas. The slopes of municipal landfills with the factor $F < 1.3$ are considered unstable in terms of stability.

The construction of municipal waste landfills in Poland is currently regulated by the Act of 14 December 2012 on waste and the Regulation of the Minister of the Environment of 30 April 2013 on landfills [15, 19]. The regulation [15] stated that the operation of the landfill should ensure "geotechnical stability of the stored waste", however, the method of ensuring this has not been defined. The slopes of the landfill in the post-operational phase should also be subject to the assessment of stability "determined by geotechnical methods".

The aim of the work is to verify the stability of municipal waste stored in a landfill of a specific structure, assuming variables related to the waste massif, such as height, width of the crest and slope inclination of the massif. Two different materials were considered as a mineral sealing layer: compacted highly plastic clay and compacted fly ash that meets the conditions of the material for the construction of the sealing layer [20, 23]. The analysis may be helpful in determining a procedure for waste placement storage.

2. MATERIALS AND METHODS

2.1. Geometry of the analyzed slope and materials

In the ground, under the landfill and its side walls, there should be a natural geological barrier in the form of a continuous layer of soil with a permeability coefficient $k \leq 10^{-9}$ m/s [2, 11, 14, 25]. In the case of the absence of a suitable natural geological barrier, an artificial barrier is made. The natural or artificial barrier is accompanied by a synthetic geomembrane. The base of the municipal waste landfill and its slopes are also equipped with a drainage system for leachate. According to [15], the minimum thickness of the natural geological barrier should not be less than 1.0 m, and the artificial mineral barrier should be at least 0.5 m thick. Drainage layers are designed from soil materials with a permeability coefficient $k > 10^{-4}$ m/s and a thickness of not less than 0.5 m.

The landfill was assumed as a sub-level in the excavation, where the maximum height of the waste is equal to the height of the excavation slope. The slope of the excavation is made of fine sand. Variable geometrical parameters of the municipal waste massif were assumed, such as the height of the waste massif $H = 5$, 10, 30 and 50 m, the width of the waste massif crest $B = 10$ and 50 m and the inclination of the waste massif $\alpha = 20$, 25, 30 and 45°. The shape of the excavation was adopted according to [13], with an inclination of the excavation bottom of 2% (1.1°). Figure 1 shows a scheme for municipal waste storage in a landfill.

The sealing layers of the base and slopes of the municipal waste landfill were adopted in accordance with applicable legal regulations and literature recommendations. The drainage layer is planned of medium-dense sand with 0.5 m, while the mineral sealing layer with 1 m is made of compacted stiff highly plastic clay. It should be noted that the optimum moisture content (w_{opt}) of the mineral sealing soils with high plasticity is lower than their plastic limit (w_P) [21]. In addition, a synthetic barrier is provided in the form of a double-sided textured HDPE geomembrane, 2.0 mm thick, and a non-woven geotextile with drainage and protective functions. The calculations were carried out not only for the classic mineral sealing in the form of compacted clay but also for compacted fly ash. The fly ash sealing layer was analyzed only in the case of a more unfavourable

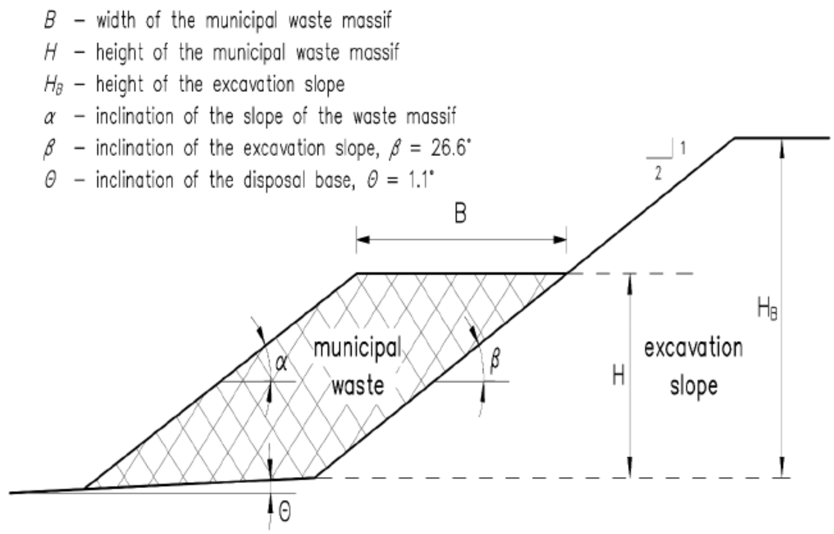

Figure 1.
Scheme of municipal waste storage at the landfill

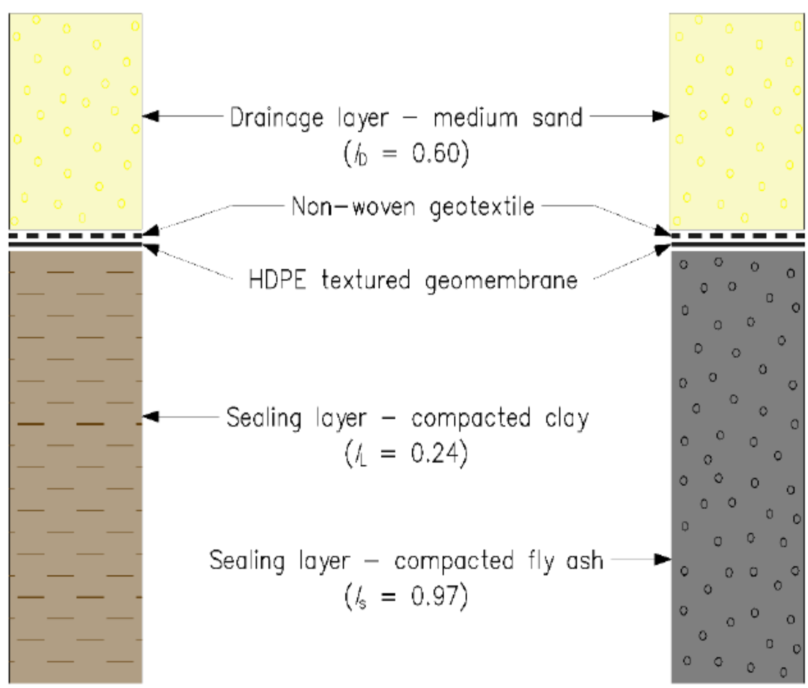

Figure 2.
Cross-section through a single-sealing layer of slope and base of the landfill made of compacted clay or compacted fly ash

design case – greater inclination and height of the waste massif. The cross-section through the layers is shown in Figure 2.

The values of geotechnical parameters of municipal waste and geosynthetic materials forming the landfill base were taken after [13]. The strength parameters of the synthetic layers were given as interface contact parameters, which were presented as peak strength values at maximum shearing resistance. Earlier authors' research [18, 24] showed that the main failure mechanism took place in the base of the filled landfill, so peak values were used for calculation. The peak strength parameters are generally used in landfill base stability analyses when the residual values are used for the calculation of the stability of multilayer surface sealings [17]. Sliding resistance is not taken into consideration. Interface unit weights were taken as an arithmetic mean of the weights of two adjacent materials. The fly ash parameters were given after [21, 22] for the material characterized by the lowest hydraulic conductivity that was established at w_{opt}+5%. The parameters of the applied materials are presented in Tables 1 and 2.

The soil and water conditions in the subsoil were assumed to be simple. Near-surface formations are non-cohesive sandy soils in the form of medium sands at medium dense, also lying deeper in the subgrade. Below the non-cohesive formations, there are glacial clayey soils in the form of stiff sandy clays and clays. The presence of groundwater and leachate levels is not assumed in the analyzed subsoil.

Table 1.
Parameters of materials used for calculations of waste landfill stability

Layer number	Material	γ (kN/m^3)	ϕ/δ (°)	c/c_a (kPa)
I	Municipal waste	10.20	30.0	3.0
II	Medium sand I_D=0.60	16.68	33.6	–
III	Medium sand + Non-woven geotextile	9.02	27.0	14.0
IV	Non-woven geotextile + Textured geomembrane HDPE	5.29	24.0	0.0
V	Textured geomembrane HDPE + Compacted clay	14.91	19.0	9.3
VI	Compacted clay I_L=0.24	20.60	17.5	30.1

Explanation: I_D – the density index (the relative density), I_L – the plasticity index, γ – the unit weight, ϕ and δ – the internal and interface friction angle, respectively, c and c_a – the cohesion and adhesion, respectively.

Table 2.
Parameters of materials used for alternative calculations of waste landfill stability

Layer number	Material	γ (kN/m^3)	ϕ/δ (°)	c/c_a (kPa)
V	Textured geomembrane HDPE + Compacted fly ash	11.77	12.0	10.0
VI	Compacted fly ash R=0.97	14.32	40.0	42.0

Explanation: R – the relative compaction (% of maximum compaction)

2.2. Methods of calculations

Landfill slope stability is typically assessed using limit equilibrium methods. The most used methods are the classic limit equilibrium methods: Fellenius, Bishop, Janbu, or Morgenstern-Price. When performing calculations according to the recommendations of Eurocode 7 [4], it should be considered that the Eurocode imposes the assumption of horizontal forces between vertical stripes, which excludes the use of the Fellenius method. In the Fellenius method, zero shear and normal forces are assumed between the calculation blocks, which results in lower values of the obtained stability factors. Additionally, the heterogeneity of municipal waste deposited in the landfill increases the range of generated errors, so the Fellenius method can only be used for an approximate forecast of the stability of landfill slopes [8].

The most unfavourable circular slip surfaces of 45 construction variants of municipal waste massifs at two different constructions of landfill slope and base sealing layers, were analyzed. The considerations were carried out according to approach 3 (DA3) of Eurocode 7 [1, 4], approved according to the National Annex for checking the state of equilibrium (stability) and determining the degree of utilization. Stability calculations were also made considering the values of safety factors, i.e., using the characteristic values of parameters and actions.

The value of the degree of utilization (utilization factor) for the ultimate limit state GEO according to Eurocode 7 [1, 4] is given by the formula (1):

$$\Lambda = \frac{E_d}{R_d} \cdot 100\% < 100\% \tag{1}$$

where: E_d – the design destabilizing effects of actions, and R_d – the design stabilizing effects (resistance). The design is unacceptable if the degree of utilization is > 100%.

Comparatively, the results are presented as values of the factor of safety (F):

$$F = \frac{R_k}{E_k} > F_p \tag{2}$$

where: R_k – the characteristic stabilizing resistances, E_k – the characteristic destabilizing effect of actions, and F_p – the permissible value of the stability factor.

The structure stability analysis was performed using the GEO5 numerical program (Slope Stability module), considering the limit equilibrium methods: Fellenius/Petterson, Bishop, Spencer, Janbu and Morgenstern-Price, assuming a circular slip surface. The calculations were carried out several times, looking for the slip surface with the lowest factor of safety, called critical slip surface [5].

3. ANALYSIS OF CALCULATION RESULTS

The calculation results are presented, depending on the geometry of the slope and the calculation method in Table 3 for compacted clay as a material in sealing, and Table 4 – for fly ash as a part of sealing. The results are shown as the degree of utilization for the limit state (*Λ*) and as the factor of safety (*F*). Parameters indicating the lack of stability of the waste massif are marked in red. Parameters differentiated for clay and fly ash are marked in bold.

Table 3.
Percentage utilization for the limit state *Λ* and factor of safety (F) depending on slope geometry and calculation method for compacted clay as a mineral sealing layer.

Geometrical parameters			Percentage utilization *Λ* (%) / factor of safety F (–) determined by the method:				
			Bishop	Fellenius/Petterson	Spencer	Janbu	Morgenstern-Price
α=20°	B=10 m	H=5 m					
		H=10 m			94.1/1.33		
		H=30 m					
		H=50 m	72.3/1.73	73.0/1.71	71.6/1.75	71.4/1.75	71.3/1.75
	B=50 m	H=5 m					
		H=10 m			94.1/1.33		
		H=30 m					
		H=50 m	70.8/1.77	72.3/1.73	70.8/1.76	70.8/1.76	70.8/1.76
α=25°	B=10 m	H=5 m					
		H=10 m			94.1/1.33		
		H=30 m					
		H=50 m	87.7/1.42	89.1/1.40	87.3/1.43	87.2/1.43	87.2/1.43
	B=50 m	H=5 m					
		H=10 m			94.1/1.33		
		H=30 m					
		H=50 m	88.8/1.41	90.9/1.38	88.9/1.41	88.9/1.41	88.9/1.41
α=30°	B=10 m	H=5 m			94.1/1.33		
		H=10 m					
		H=30 m	97.0/**1.29**	**97.9/1.28**	**98.7/1.27**	**98.1/1.27**	98.4/1.27
		H=50 m	–	–	–	–	–
	B=50 m	H=5 m			94.1/1.33		
		H=10 m					
		H=30 m	102.0/1.22	105.4/1.19	102.1/1.22	102.1/1.22	102.1/1.22
		H=50 m	107.5/1.16	110.3/1.13	107.6/1.16	107.6/1.16	107.6/1.16
α=45°	B=10 m	H=5 m	99.5/1.26	106.2/1.18	99.8/1.25	99.8/1.25	99.2/1.26
		H=10 m	133.6/0.94	137.7/0.91	133.1/0.94	**132.7**/0.94	132.8/0.94
		H=30 m	–	–	–	–	–
		H=50 m	–	–	–	–	–
	B=50 m	H=5 m	105.3/1.19	110.4/1.13	105.7/1.18	**105.7/1.18**	105.2/1.19
		H=10 m	126.5/0.99	132.7/0.94	127.0/0.98	126.9/0.98	127.0/0.98
		H=30 m	158.8/0.79	165.4/0.76	159.2/0.79	159.3/0.78	159.2/0.79
		H=50 m	171.5/0.73	178.4/0.70	**171.9**/0.72	171.8/0.73	171.8/0.73

Table 4.
Percentage utilization for the limit state (*Λ*) and factor of safety (F) depending on slope geometry and calculation method for compacted fly ash as a mineral sealing layer

Geometrical parameters			Percentage utilization *Λ* (%) / factor of safety F (–) determined by the method:				
			Bishop	Fellenius/Petterson	Spencer	Janbu	Morgenstern-Price
α=30°	B=10 m	H=5 m			94.1/1.33		
		H=10 m					
		H=30 m	97.3/**1.28**	**99.7/1.25**	**99.6/1.25**	**99.1/1.26**	98.4/1.27
		H=50 m	–	–	–	–	–
	B=50 m	H=5 m			94.1/1.33		
		H=10 m					
		H=30 m	102.0/1.22	105.4/1.19	102.1/1.22	102.1/1.22	102.1/1.22
		H=50 m	107.5/1.16	110.3/1.13	107.6/1.16	107.6/1.16	107.6/1.16
α=45°	B=10 m	H=5 m	99.5/1.26	106.2/1.18	99.8/1.25	99.8/1.25	99.2/1.26
		H=10 m	133.6/0.94	137.7/0.91	133.1/0.94	**132.6**/0.94	132.8/0.94
		H=30 m	–	–	–	–	–
		H=50 m	–	–	–	–	–
	B=50 m	H=5 m	105.3/1.19	110.4/1.13	105.7/1.18	**105.1/1.19**	105.2/1.19
		H=10 m	126.5/0.99	132.7/0.94	127.0/0.98	126.9/0.98	127.0/0.98
		H=30 m	158.8/0.79	165.4/0.76	159.2/0.79	159.3/0.78	159.2/0.79
		H=50 m	171.5/0.73	178.4/0.70	**172.4**/0.72	171.8/0.73	171.8/0.73

In the vast majority of calculation cases, slightly lower values of the factors of safety F and greater degrees of utilization were obtained using the Fellenius/Petterson method, due to the assumption of zero shear and normal forces between the design blocks. The dimensions and shape of the mass of waste which are assessed as stable according to other methods, in the case of the Fellenius method, they are evaluated as unstable (underestimation of the factor of safety and overstatement of the degree of utilization). Earlier literature reports indicated much lower F values in the case of the Fellenius method compared to other methods than those obtained for the slope of municipal waste lined with a sealing layer.

Analyzing the calculations made in accordance with DA3 of Eurocode 7 [4], it was found that with the assumed structure and geometric dimensions of the landfill, the waste mass can be considered stable at the storage height H = 5 – 50 m, the width of the crown of the waste lump B equal to 10 and 50 m and the slope inclination waste massif α from 20° to 25°, independently on kind of sealings. After increasing

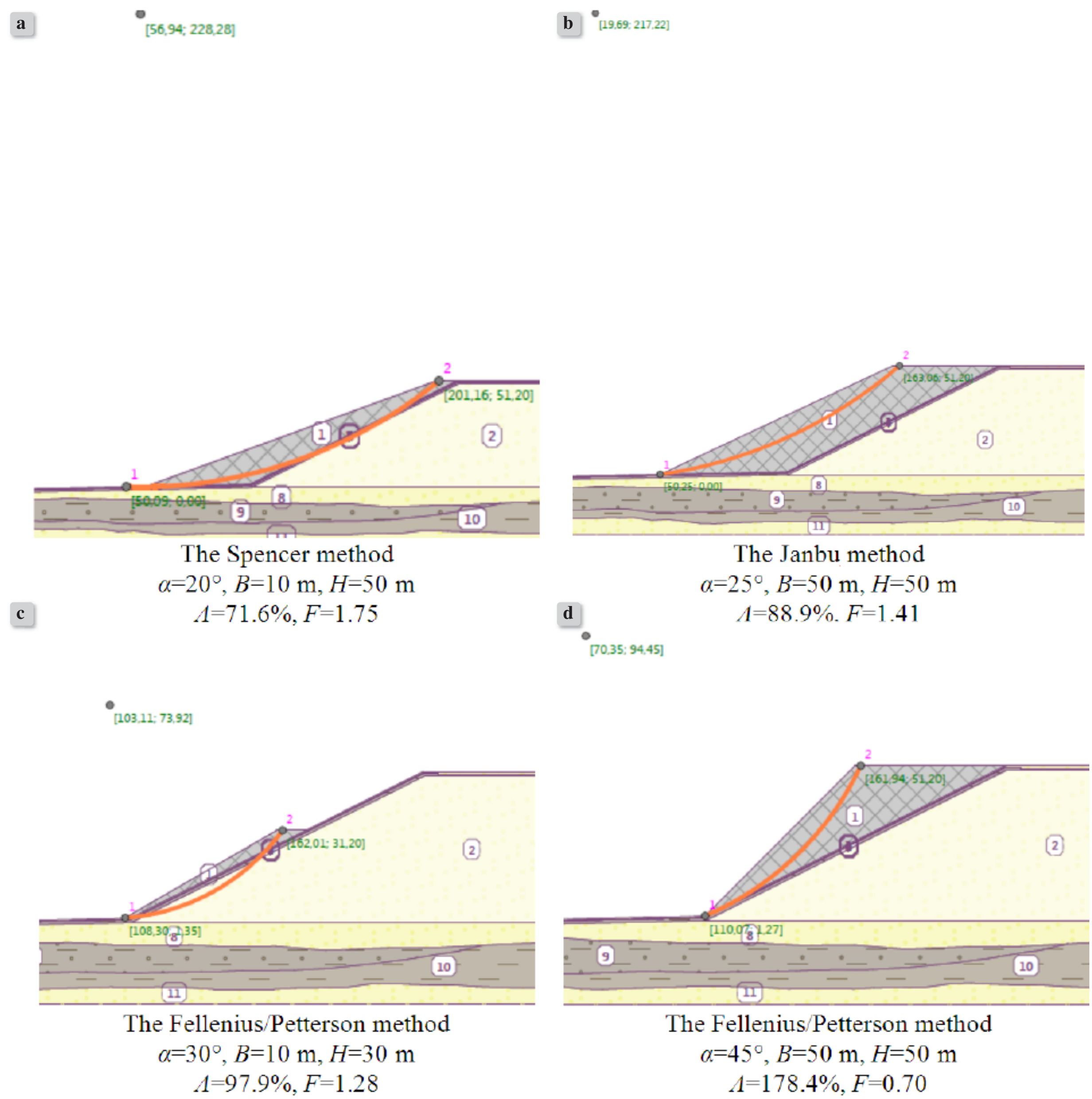

Figure 3.
Examples of slip surfaces generated with the GEO5 program for classic clay mineral sealing layer: a), b), c) the stability of the structure is preserved, d) the stability of the structure was not preserved

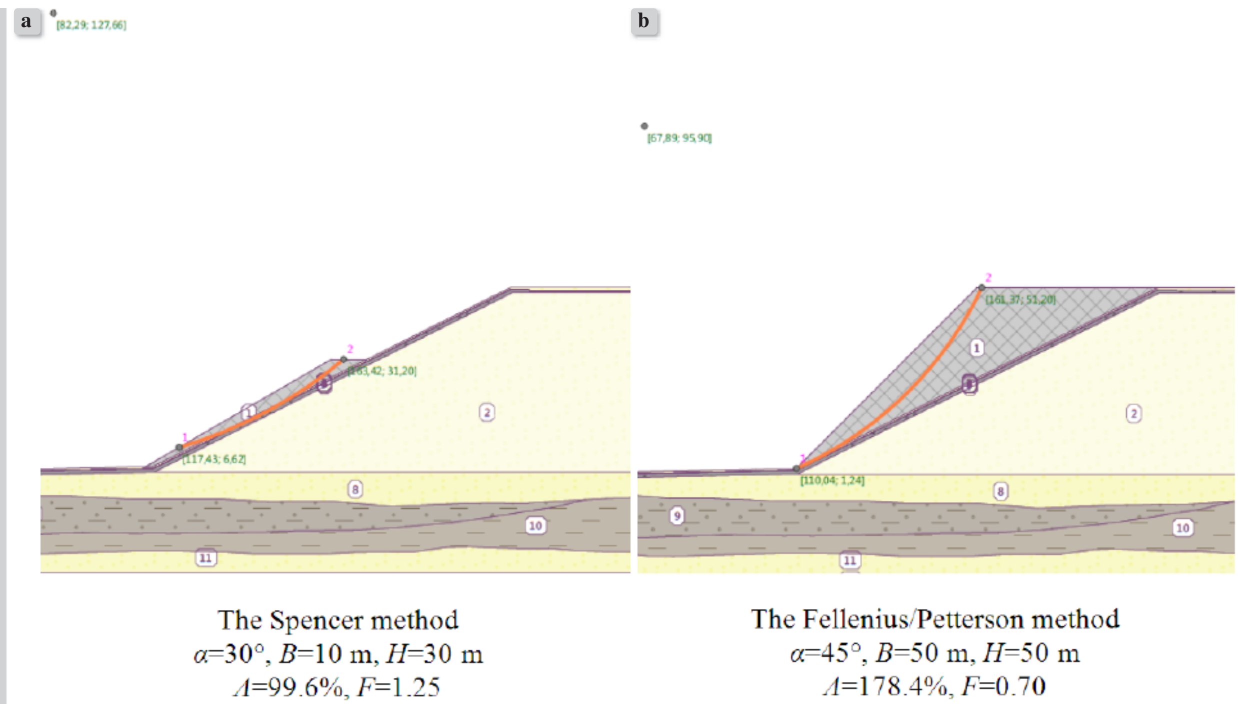

Figure 4.
Examples of slip surfaces generated with the GEO5 program for fly ash as a mineral sealing layer: a) the stability of the structure is preserved, b) the stability of the structure was not preserved

the inclination of the waste slope to 30°, the slope is stable at $B = 10$ m, and when $B = 50$ m – only at the height of waste storage $H = 5 – 10$ m. In the case of a further increase of the slope inclination α to 45°, the stability condition is met only with the width of the slope equal to 10 m and the height H of the stored waste equal to 5 m.

Stability calculations considering the factor of safety may be more or less rigorous compared to the calculations according to Eurocode 7 (DA3), depending on the permissible value of the stability factor adopted. Assuming that the factor of safety should be $F_p = 1.2-1.3$ [8, 10], structures of waste slopes with the slope of the waste massif $\alpha \geq 45°$ and crown width $B = 50$ m can be considered unstable, while in the case of $B = 10$ m, the slopes up to a height of 10 m are stable. The stability condition is also not checked by slopes with an inclination of $\alpha = 30°$, a crest width of $B = 50$ m and a height of 50 m. These conditions are practically identical to the calculations according to Eurocode 7. Considering that F_p should be at least equal to 1.3, the stability condition is met only by the construction of slopes with an inclination of $\alpha \leq 25°$, in the case of both the width of the crown and the height of the massif $H \leq 50$ m. Slopes with a greater inclination $\alpha = 30°$ meet the condition stability if the height of the stored waste is 10 m or less.

In the case of the analyzed slope inclination α equal to 20° and 25°, the increase in the height of the stored waste does not reduce the stability of the waste mass. The height of the slope starts to affect the stability of the waste at $\alpha = 30°$ and height $H = 30-50$ m, to reach full impact at $\alpha = 45°$.

It should be noted that the location of the critical slip lines varies depending on the geometrical dimensions of the waste body, and is generally independent of the adopted calculation method. However, the location of the slip line is affected by the type of layer sealing the slope and the base of the landfill. In the case of classic clay sealing, the slope inclination $\alpha = 20°-25°$ and the height of the massif $H = 5-30$ m, the slip plane runs in the sealing of the excavation slope, regardless of the width of the waste massif. After increasing H to 50 m, when $B = 10$ m, circular slip lines go along the slope seal (Fig. 3a), but when B = 50 m lines go across waste massif (Fig. 3b). At slope inclination $\alpha = 30°$ the slip line crosses sealing at excavation slope when $H = 30$ m and $B = 10$ m (Fig. 3c), and when $H = 30 – 50$ m and B = 50 m – runs across waste. In the case of inclination $\alpha = 45°$ the circular slip line appears in the waste massif from the value of $H = 5$ m, and the structure is not stable (Fig. 3d).

In the case of sealing with fly ash as the mineral layer of the sealing, similar courses of circular slip lines (Fig. 4) and mostly identical values of safety factors and utilization degrees were obtained, within the scope of calculations performed (Tables 3 and 4). Variation of the slip line was observed in the case of the slope inclination $\alpha = 30°$ and massif shape determined by $B = 10$ m, $H = 30$ m. For fly ash sealing the slip line does not cross the sealing but goes along the sealing (Fig. 4a), but in both cases the structure is stable.

4. CONCLUSIONS

1. Calculations of the slope stability of municipal waste stored in landfills were made in accordance with the recommendations of approach 3 (DA3) for the ultimate limit state GEO of Eurocode 7 and by analyzing safety factors. Evaluation of slope stability using both methods is comparable if the permissible values of factors of stability are greater than 1.2. If $F_p \geq 1.3$, the stability analyses using the factor of safety are much more rigorous than in the case of limit state and degree of utilization.
2. Municipal waste stored in a sub-level landfill is generally stable if the inclination of the waste slope is $\alpha \leq 25°$. The height of the stored waste can then be even 50 m, with a crest width of 50 m. When the slope inclination is $\alpha = 30°$, the structures of waste massifs up to a height of 10 m are stable. These values were assessed independently on the tested material of mineral sealing.
3. The given values of geometrical parameters of the stored waste should be treated as indicative only, due to the large diversity of physical and mechanical parameters of municipal waste and their heterogeneity.
4. Using the Fellenius/Petterson method can lead to an underestimation of the factor of safety and an overstatement of the degree of utilization, and consequently to incorrect assessment of the safety of the structure. Other methods of assessing structure stability – the Bishop, Janbu, or Morgenstern-Price methods give comparable or the same results.
5. The use of various stability assessment methods (the Fellenius/Petterson, Bishop, Janbu, or Morgenstern-Price methods) leads to very similar circular slip lines. Changing the material of the mineral sealing layer can lead to a change in the course of the circular slip line.

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