



## Research paper

# Impact of calculation method on results of stability analysis of stored municipal waste

Katarzyna Zabielska-Adamska<sup>1</sup>, Justyna Markowska<sup>2</sup>

**Abstract:** The paper presents a stability analysis of a municipal waste landfill lined by a single-drainage and mixed sealing layer. The drainage layer is medium-dense sand, while the mixed sealing layer consists of compacted stiff highly plastic clay and a synthetic barrier in the form of a double-sided textured HDPE geomembrane. Beneath a sealing, there is a non-woven geotextile with drainage and protective functions. 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. Variable geometrical parameters of the municipal landfill were assumed, such as the height, the width and the inclination of the waste body. The structure stability analysis was performed using the GEO5 numerical programme. The calculations were carried out several times, looking for the most unfavourable slope surface. The considerations were conducted for checking the state of equilibrium (stability) according to design approach 3 (DA3) of Eurocode 7, approved according to the Polish National Annex and accepted in most CEN countries, and according to approach 1 (DA1) and 2 (DA2) adopted in other CEN countries. The values of the degree of utilization (utilization factor) for the ultimate limit state GEO according to Eurocode 7 were given. Stability calculations were also made considering the values of safety factors, i.e., using the characteristic values of parameters and actions. The values of the utilization factors achieved in all design approaches and the safety factor were compared.

**Keywords:** analysis of slope stability, Eurocode approaches, mixed sealing of landfills, storage of municipal waste, waste stability calculations

<sup>1</sup>Prof., DSc., PhD., Eng., Białystok University of Technology, Faculty of Civil Engineering and Environmental Sciences, ul. Wiejska 45E, 15-351 Białystok, Poland, e-mail: [kadamska@pb.edu.pl](mailto:kadamska@pb.edu.pl), ORCID: 0000-0003-2823-6595

<sup>2</sup>MSc., Eng., Doctoral School of Białystok University of Technology, ul. Wiejska 45A, 15-351 Białystok, Poland, e-mail: [justyna.markowska@sd.pb.edu.pl](mailto:justyna.markowska@sd.pb.edu.pl), ORCID: 0009-0002-2072-3882

## 1. Introduction

Limit states for slopes generally comprise loss of overall stability of the ground and associated structures, excessive movement, or loss of serviceability. Slope stability includes a translational slab sheet or block slide on a weak stratum, circular and non-circular slides, and a large slide encompassing a supporting structure. Based on [1], it can be noticed that the calculation of slopes seems to be a debatable design situation. In the European Union, the most popular design approach for slopes is approach 3 (DA3), adopted by 65% of CEN countries, followed by approach 1 (DA1) – 25%. Only one country – Spain – has chosen approach 2 (DA2), while Ireland accepts using any design approach. National choices of design approach for slopes are presented in Fig. 1.

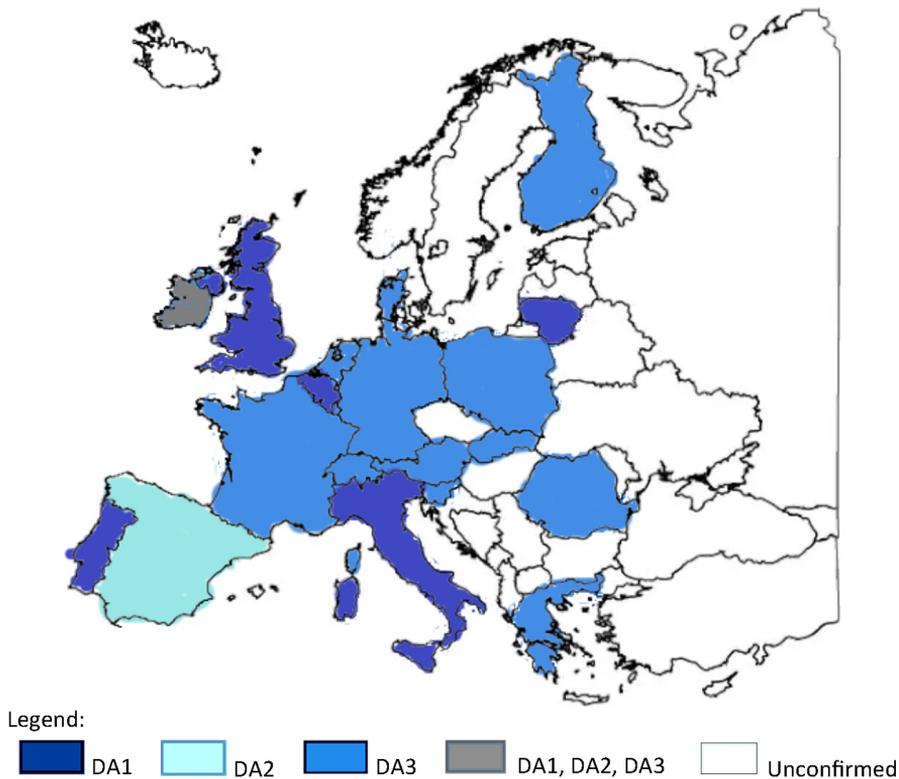


Fig. 1. National choices of design approach for slopes after [1]

Table 1 shows differences in DAs in the calculations of slopes. DA1 is used for checking the structure's reliability in two stages. Combination 1 in DA1 is used for actions, while ground material properties and resistances are unfactored, so partial factor sets M1 and R1 are equal to 1.0. Combination 2 is used for ground strength variables, so sets A2 and R1 are 1.0. DA2 is engaged to check the structure's reliability where ground material properties are unfactored and a set M1 is 1.0. In DA3 partial factors for structure's reliability are given to actions and

ground strength properties, so a set R3 is 1.0. DA3 is similar to DA1, but calculations are done in a single phase. The partial factors according to EC7 [2] for GEO/STR in the case of slopes are shown in Table 2. It can be seen that the values of the partial factors of DA1 (combination 2) and DA3 are identical. Both design approaches rely on the design material properties (M2) as the primary variable, reduced by dividing by partial factors for mechanical properties.

Table 1. Sets of partial factors used in each design approach [2] and their main variables for the GEO/STR limit states after [1]

DA1		DA2	DA3
Combination 1	Combination 2		
<b>A1</b> + M1 + R1	A2 + <b>M2</b> + R1	<b>A1</b> + M1 + <b>R2</b>	A2 + <b>M2</b> + R3
The primary variable in DAs			
Actions	Material properties	Effects of actions and resistance	Structural effects of actions and material properties

Explanations: Sets A applied to actions, M to material properties, and R to resistance. The primary variable is bolded.

Table 2. Sets of partial factors used in EC7 [2] for GEO/STR

Parameter in slopes		Actions or effects		Material properties		Resistance							
		A1	A2	M1	M2	R1	R2	R3					
Permanent action	Unfavourable	1.35	1.0										
	Favourable	1.0	1.0										
Variable action	Unfavourable	1.5	1.3										
	Favourable	0	0										
Coefficient of shearing resistance									1.0	1.25			
Effective cohesion									1.0	1.25			
Unit weight				1.0	1.0								
Earth resistance						1.0	1.1	1.0					

According to [1] DAs 1 and 3 produce almost identical results when applied to slope stability, so almost all European countries have adopted a common approach for this issue, which the authors decided to check in a complicated design situation – the landfill lined by mixed barrier.

The work aims to verify the stability of municipal waste stored in a landfill of a given shape with adopted parameters of the waste body, such as height, width of the crest and slope inclination, sealing the base and slopes of the landfill, and given ground conditions beneath the landfill. Calculations have been done using three design approaches: DA1, DA2 and DA3. Additionally, the results are presented as values of the safety factor (F).

## 2. Literature review on waste and landfills

Factors affecting landfill slope stability [3] can be divided into internal (geological) and external (geo-environmental). More detailed internal factors can be reviewed as waste engineering properties (composition and structure, physical and mechanical properties) and structural features of the waste body (geometrical dimensions, leachate and landfill gas). External factors are represented by dynamic engineering geological processes (earthquake, rainfall, leachate recirculation, toe excavation and overload). Significant elements affecting the stability of the landfill are the geometric dimensions (height, width and inclination of the waste body slope), as well as waste physical and mechanical parameters. One pays attention to waste composition, particle size, degree of degradation, and moisture content [4]. All these parameters influence landfill stabilization. Conventional landfills require 50 years or longer to be bio-stabilized [5]. It is known that total degradation of the waste mass can produce settlements approaching 30% of the waste body height.

Municipal waste collected in landfills is a material that is very diverse in terms of morphology and density. Fresh municipal waste is characterized by a density ranging from 0.4–1.0 Mg/m<sup>3</sup>, while landfill waste has a density of 0.8–1.2 Mg/m<sup>3</sup> [6]. The dry density of fresh waste is obtained in the range of 0.10–1.44 Mg/m<sup>3</sup> and decreases after compaction even twice [7]. The shear strength of municipal waste changes over time, which is primarily related to its compression and decomposition of organic matter. The time of about 1.5–3 years after the ending of deposition relates to a change in the intensity of the processes of biodecomposition [8]. There is also a gradual decrease in the strength parameters of municipal waste due to waste succeeding decomposition.

The most common ranges of strength parameters [9] are about 20–35° for the angle of internal friction,  $\varphi$ , and 15–40 kPa for the cohesion resistance,  $c$ . The slightly different values of strength parameters are given by Dixon et al. [10]: 15–42° for the angle of internal friction and 0–28 kPa for cohesion intercept. Bareither et al. [7] placing together the values of the strength parameters from literature data, obtained similar values for the angle of internal friction as 19.0–43°, but nearly 2.5 times greater values of cohesion 0–64 kPa. Values of the shear parameters differ meaningfully in tests of segregated waste, such as:  $\varphi$  for plastic equals 18° and for paper is 33° [11]. Another problem is the range of normal stress during the tests. Many researchers reported a bilinear or even – trilinear failure envelope obtained during shearing. Only Zekkos et al. [12] assessed the angle of internal friction of 15-year-old waste as 32.3–33° and cohesion 21.0–23.4 kPa in wide-ranging normal stress 2–700 kPa. Moreover, saturation negatively affects the stability of slopes [13]. Care must be taken when assuming pore pressure conditions and assigning a unit weight to the waste material because the safety factor depends principally on the value assigned to these parameters [4].

Sealing the base and slopes of the landfill, used for protection against the penetration of leachates and landfill gases into the ground and groundwater, is another problem with landfill stability. A natural geological barrier in the form of a continuous layer of soil with a permeability coefficient  $k \leq 10^{-9}$  m/s [14–17] should line the bottom of the landfill and its side walls. In the case of the absence of a suitable natural geological barrier, an artificial barrier is constructed. The natural or artificial barrier is combined with a synthetic geomembrane. Nowadays, the most often used high-density polyethylene (HDPE) geomembranes are produced with textured surfaces to prevent slippage along mixed seal phases.

Council Directive on the landfill of waste [18] determines the base and sides of landfill for non-hazardous waste should consist of a mineral layer with  $k = 10^{-9}$  m/s and a minimum thickness of 1 m. An artificial sealing layer and drainage layer are required.

It should be noted that due to the diversity of landfill types and highly variable composition of waste, the assumed parameters for the design of landfill sites can be highly uncertain and unreliable, so it is recommended to conduct a site-specific investigation to obtain the required materials properties for more reliable design and construction [19].

### 3. Materials and methods

#### 3.1. Analysed slope geometry and materials

The soil and water conditions in the subsoil beneath the landfill have been assumed to be simple. The subgrade consists of non-cohesive sandy soil in the form of medium sand of medium density, and beneath are glacial clayey soils in the form of stiff sandy loams and clays. The groundwater table and leachate level are not assumed in the analyzed subsoil. The tested landfill is undertaken as a sub-level in an excavation, where the maximum waste height is equal to the height of the excavation. The slope of the excavation is built of fine sand. The sealing layers of the base and slopes of the landfill were taken following appropriate legal regulations and literature recommendations [14–18]. The mineral sealing layer was made of stiff, highly plastic clay compacted at a moisture content greater than optimum with a permeability coefficient  $k \leq 10^{-9}$  m/s. The thickness of the clay layer was 1.0 m. It should be mentioned that clay moisture content during compaction strictly influences its hydraulic conductivity [20]. The drainage layer was made of medium-dense sand with 0.5 m thick and permeability coefficient  $k > 10^{-4}$  m/s. The sealing system was accompanied by geosynthetic materials: non-woven geotextile with drainage and protection functions and 2.0 mm thick double-sided textured high-density polyethylene (HDPE) geomembrane as a barrier. The cross-section through the layers is shown in Fig. 2.

The different geometrical parameters of the municipal waste body have been assumed, such as the height of the waste  $H = 5, 10, 30$  and  $50$  m, the width of the waste  $B = 10$  and  $50$  m and the inclination of the waste body  $\alpha = 20^\circ, 25^\circ, 30^\circ$  and  $45^\circ$ . The shape of the excavation was adopted after [21], with an inclination of the excavation bottom of 2%. Figure 3 shows a scheme of the municipal waste landfill.

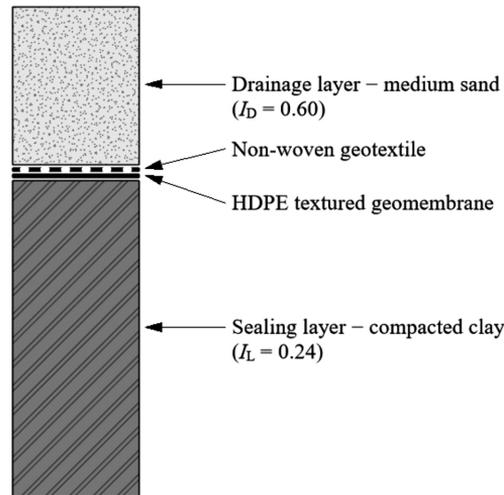


Fig. 2. Cross-section through the slope and base of the landfill

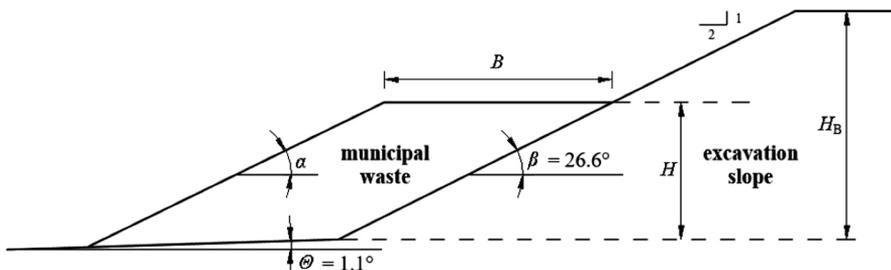


Fig. 3. Waste storage at the landfill, where  $B$  and  $H$  are the width and height of the waste body,  $\alpha$ ,  $\beta$  and  $\theta$  are the inclination of the waste slope, excavation slope and disposal base, and  $H_B$  is the height of the excavation

Test results of shear strength parameters of the contact soil–geosynthetic, interface friction angle,  $\delta$ , and adhesion,  $c_a$ , are generally presented for the peak (maximum contact resistance at the moment of shearing) and residual values (steady-state value of shearing resistance). The peak strength parameters are commonly used in landfill base stability analyses, while the residual values are used for the stability calculation of the multi-layer surface or slope-side sealings [22, 23]. In the study, the strength parameters of the synthetic layers were given as peak interface contact parameters at maximum shearing resistance, because earlier authors' research [24, 25] showed that the principal failure mechanism took place in the base of the packed landfill. Sliding resistance and settlement of waste body are not taken into account here. The values of geotechnical parameters of municipal waste and geosynthetics constructing the landfill sealing system were given after [21]. Interface unit weights were an arithmetic mean of the weights of two adjacent materials. The physical and mechanical parameters of the adopted materials or interface contacts are presented in Table 3.

Table 3. Material parameters taken into calculations

Calculation layer or interface	$\gamma$ (kN/m <sup>3</sup> )	$\varphi$ (°)	$\delta$ (°)	$c$ (kPa)	$c_a$ (kPa)
Municipal waste	10.20	30.0	–	3.0	–
Medium sand $I_D = 0.60$	16.68	33.6	–	–	–
Medium sand + non-woven geotextile	9.02	–	27.0	–	14.0
Non-woven geotextile + textured geomembrane HDPE	5.29	–	24.0	–	0.0
Textured geomembrane HDPE + compacted clay	14.91	–	19.0	–	9.3
Compacted clay $I_L = 0.24$	20.60	17.5	–	30.1	–

Explanations:  $\gamma$  – the unit weight,  $\varphi$  – the internal friction,  $c$  – the cohesion resistance,  $\delta$  – the interface friction angle,  $c_a$  – the adhesion.

### 3.2. Calculation methods

To analyze the stability of landfills limit equilibrium methods based on a cylindrical (circular) slip surface and the finite element method (FEM) are used, e.g. [16, 21, 26–29]. Landfill slope stability is usually valued by limit equilibrium methods and most often by the classic limit equilibrium methods: Fellenius, Bishop, Janbu, or Morgenstern–Price. Calculations following Eurocode 7 [2] should consider that the Eurocode obliges the assumption of horizontal forces between vertical stripes. That excludes the use of the Fellenius method, where zero shear and normal forces are assumed between the calculation blocks, which results in lower stability factor values. Furthermore, the heterogeneity of municipal waste dumped in the landfill generates additional errors, so the Fellenius method can only be used for a stability prediction of the landfill slopes [26]. On the other hand, the Fellenius method may be helpful in a rough analysis of existing landfills.

The analysis was carried out according to three design approaches of Eurocode 7: DA3 approved in the Polish National Annex for checking the state of equilibrium (stability), besides DA1 and DA2 used in other European countries. The degree of utilization was calculated for each of the considered cases. Calculations were also made considering the values of safety factors, i.e., using the characteristic values of parameters and actions. The most unfavorable circular slip surfaces were analyzed, considering 29 options of waste body geometry per design approach/factor of safety and five different methods of calculations.

The degree of utilization (utilization factor) value for the ultimate limit state GEO after Eurocode 7 [1, 2] is given by Eq. (3.1):

$$(3.1) \quad A = \frac{E_d}{R_d} \cdot 100\% < 100\%$$

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 shown as the factor of safety ( $F$ ) values, given by Eq. (3.2):

$$(3.2) \quad F = \frac{R_k}{E_k} > F_p$$

where:  $R_k$  – the characteristic stabilizing resistances,  $E_k$  – the characteristic destabilizing effect of actions, and  $F_p$  – the acceptable value of the safety factor.

In the most used limit equilibrium methods, the factor of safety ( $F$ ) is to be greater than the acceptable value of the stability factor. In the case of the municipal waste landfill, it should be taken 1.2 or 1.3, depending on the importance of the facility and threats to adjacent areas [26]. According to [1], the safety factor varies between 1.3 and 3.0, depending on the structure and failure type.

The landfill stability analysis was performed using the GEO5 numerical programme (Slope Stability module), considering the limit equilibrium methods: Fellenius/Petterson, Bishop, Spencer, Janbu and Morgenstern–Price, assuming a circular slip surface. The calculations were conducted multiple times, searching the critical slip surface [30].

## 4. Calculation results and their analysis

The results of calculations are shown separately for each design approach. The degree of utilization for the limit state ( $\Lambda$ ) obtained according to DA3 of Eurocode 7, as a more popular design approach used in most European countries, including Poland, is presented in Table 4, while DA2 and DA1 are in Tables 4 and 5, respectively. They are given depending on the landfill body geometry and the calculation method. Parameters indicating the lack of stability of the landfill are marked in bold.

Table 4. Percentage utilization for the limit state  $\Lambda$  according to DA3 depending on slope geometry and calculation method

Geometry of the waste body			Percentage utilization $\Lambda$ (%) for method				
$\alpha$ (°)	$B$ (m)	$H$ (m)	Bishop	Fellenius/ Petterson	Spencer	Janbu	Morgenstern- Price
20	10	5	94.1				
		10					
		30					
		50					
	50	5	94.1				
		10					
		30					
		50					

*Table continued on the next page*

Table continued from the previous page

Geometry of the waste body		Percentage utilization $\Lambda$ (%) for method					
25	10	5	94.1				
		10					
		30					
		50	87.7	89.1	87.3	87.2	87.2
	50	5	94.1				
		10					
		30					
		50	88.8	90.9	88.9	88.9	88.9
30	10	5	94.1				
		10					
		30					
		50	–	–	–	–	–
	50	5	94.1				
		10					
		30					
		50	<b>107.5</b>	<b>110.3</b>	<b>107.6</b>	<b>107.6</b>	<b>107.6</b>
45	10	5	99.5	<b>106.2</b>	99.8	99.8	99.2
		10	<b>133.6</b>	<b>137.7</b>	<b>133.1</b>	<b>132.7</b>	<b>132.8</b>
		30	–	–	–	–	–
		50	–	–	–	–	–
	50	5	<b>105.3</b>	<b>110.4</b>	<b>105.7</b>	<b>105.7</b>	<b>105.2</b>
		10	<b>126.5</b>	<b>132.7</b>	<b>127.0</b>	<b>126.9</b>	<b>127.0</b>
		30	<b>158.8</b>	<b>165.4</b>	<b>159.2</b>	<b>159.3</b>	<b>159.2</b>
		50	<b>171.5</b>	<b>178.4</b>	<b>171.9</b>	<b>171.8</b>	<b>171.8</b>

The degree of utilization ( $\Lambda$ ) values obtained along with DA3 of Eurocode 7 (Table 4) are generally somewhat larger using the Fellenius/Petterson method, owing to zero shear and normal forces among the design blocks. The waste stored in a sub-level landfill evaluated by Bishop, Spencer, Janbu and Morgenstern–Price methods is stable, while in the case of the Fellenius/Petterson method is unstable (and the degree of utilization is overstated) only in one case when slope inclination  $\alpha = 45^\circ$ , waste width  $B = 10$  m, and its highest  $H = 5$  m. Generally, the assessed structure can be regarded as stable for the storage height  $H = 5$ – $50$  m, the width of the waste  $B$  equal to 10 and 50 m and the slope inclination  $\alpha$  from  $20^\circ$  to  $25^\circ$ . With the increase in the waste slope inclination to  $30^\circ$ , the landfill is stable when  $B$  is 10 m, but when  $B$  is 50 m, the landfill is stable at the height of waste  $H = 5$ – $10$  m. After the growth of the slope inclination  $\alpha$  to  $45^\circ$ , the landfill is stable with a waste width equal to 10 m and the height of the stored waste 5 m. For the considering slope inclination  $\alpha = 20^\circ$  and  $25^\circ$ , the increase in the waste height does not decrease its stability. The height of the slope turns to influence the landfill stability at  $\alpha = 30^\circ$  and height  $H = 30$ – $50$  m to reach the full effect at  $\alpha = 45^\circ$ .

The calculations according to DA3 give the same results regardless of the method of checking the stability in the case of the slope inclination  $\alpha$  from  $20^\circ$  to  $25^\circ$ , the width of the waste  $B$  equal to 10 and 50 m, and the storage height  $H = 5\text{--}30$  m, as well as  $\alpha = 30^\circ$  and the width of the waste  $B$  equal to 10 and 50 m, and the storage height  $H = 5\text{--}10$  m.

Table 5. Percentage utilization for the limit state  $\Lambda$  according to DA2 depending on slope geometry and calculation method

Geometry of the waste body			Percentage utilization $\Lambda$ (%) for method				
$\alpha$ ( $^\circ$ )	$B$ (m)	$H$ (m)	Bishop	Fellenius/ Petterson	Spencer	Janbu	Morgenstern- Price
20	10	5	83.7	86.2	83.8	83.7	83.6
		10	83.2	85.9	83.3	83.2	83.1
		30	82.8	83.6	82.8	82.8	82.8
		50	71.0	75.4	70.2	70.2	68.8
	50	5	83.6	86.2	83.7	83.6	83.7
		10	83.2	86.0	83.3	83.3	83.3
		30	82.8	83.7	82.8	82.8	82.8
		50	64.3	69.2	64.4	64.5	64.6
25	10	5	83.7	86.2	83.8	83.8	83.6
		10	83.2	86.0	83.3	83.3	83.3
		30	82.8	83.7	82.8	82.8	82.8
		50	81.5	82.8	81.6	81.6	81.2
	50	5	83.7	86.2	83.9	83.8	83.7
		10	83.2	86.0	83.3	83.3	83.3
		30	82.8	83.7	82.8	82.8	82.8
		50	82.0	85.3	82.8	82.8	82.8
30	10	5	83.7	86.1	83.8	83.8	83.7
		10	83.2	85.8	83.3	83.3	83.2
		30	90.1	92.3	91.1	91.2	90.4
		50	–	–	–	–	–
	50	5	83.7	86.2	83.8	83.8	83.6
		10	83.2	85.8	83.3	83.3	83.2
		30	95.5	<b>100.1</b>	95.6	95.6	95.6
		50	99.7	<b>109.4</b>	99.7	99.7	99.7

Table continued on the next page

Table continued from the previous page

Geometry of the waste body			Percentage utilization $\Lambda$ (%) for method				
$\alpha$ (°)	$B$ (m)	$H$ (m)	Bishop	Fellenius/ Petterson	Spencer	Janbu	Morgenstern- Price
45	10	5	98,1	<b>105.9</b>	98.6	98.2	98.1
		10	<b>127.7</b>	<b>132.5</b>	<b>127.2</b>	<b>127.0</b>	<b>127.1</b>
		30	–	–	–	–	–
		50	–	–	–	–	–
	50	5	<b>103.3</b>	<b>109.5</b>	<b>103.9</b>	<b>103.6</b>	<b>103.6</b>
		10	<b>121.7</b>	<b>128.8</b>	<b>122.2</b>	<b>122.2</b>	<b>122.3</b>
		30	<b>147.6</b>	<b>154.6</b>	<b>147.8</b>	<b>147.8</b>	<b>147.9</b>
		50	<b>157.1</b>	<b>163.6</b>	<b>157.3</b>	<b>157.2</b>	<b>157.3</b>

The degree of utilization ( $\Lambda$ ) values found following DA2 of Eurocode 7 (Table 5) are also slightly bigger using the Fellenius/Petterson method, like in approach 3. The waste stored in a sub-level landfill evaluated by Bishop, Spencer, Janbu and Morgenstern–Price methods is stable, while in the case of the Fellenius/Petterson method is unstable in three cases when: slope inclination  $\alpha = 30^\circ$  and waste width  $B = 50$  m, and its height  $H = 30$ – $50$  m, as well as  $\alpha = 45^\circ$  and  $B = 10$  m, and its height  $H = 5$  m. Generally, the tested structure is stable in a broader range of the geometrical conditions (omitting the Fellenius/Petterson method, which is not recommended in Eurocode 7 calculations [2]) than in the case of DA3, i.e. for slope inclination  $\alpha = 20$ – $30^\circ$  and waste width  $B = 10$  and  $50$  m, and its height  $H = 5$ – $50$  m, but also for  $\alpha = 45^\circ$  and  $B = 10$  m, and its height  $H = 5$  m.

The calculations according to DA2 give different results for each stability-checking method in all design cases.

Figure 4 shows circular slip surfaces obtained by the Bishop method for the same landfill geometry for DA3 when the stability condition is not met and for DA2 when the condition is met. In both calculation approaches, the slip surface runs within the waste body.

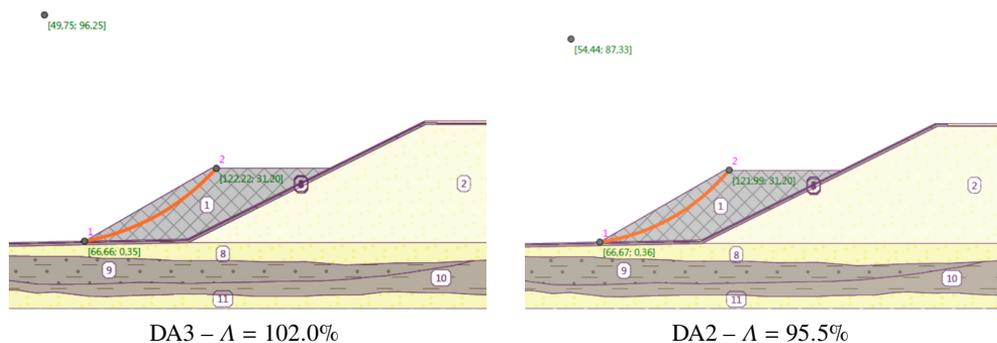


Figure continued on the next page

Figure continued from the previous page

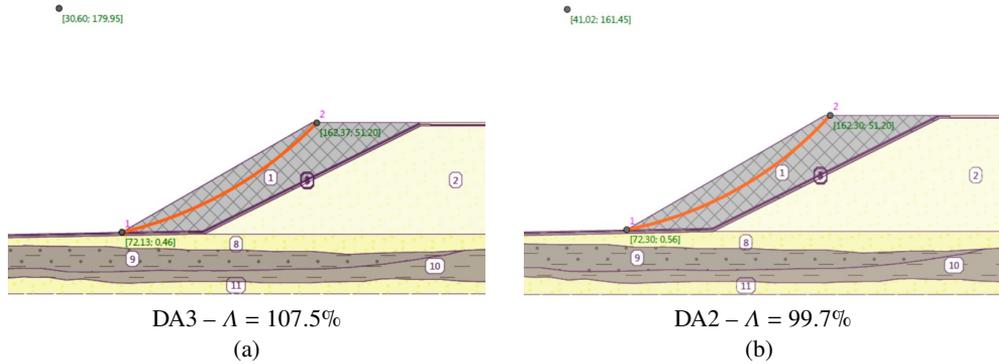


Fig. 4. Examples of slip surfaces generated with the GEO5 programme by the Bishop method for  $\alpha = 30^\circ$ ,  $B = 50$  m,  $H = 30$  m, and for  $\alpha = 30^\circ$ ,  $B = 50$  m,  $H = 50$  m: (a) the stability of the structure is not preserved (DA3); (b) the stability of the structure was preserved (DA2)

Table 6. Percentage utilization for the limit state  $\Lambda$  according to DA1 depending on slope geometry and calculation method

Geometry of the waste body			Percentage utilization $\Lambda$ (%) obtained for combinations 1/2 for method				
$\alpha$ (°)	$B$ (m)	$H$ (m)	Bishop	Fellenius/Petterson	Spencer	Janbu	Morgenstern-Price
30	10	5	76.0/94.1	78.3/94.1	75.3/94.1	76.2/94.1	76.1/94.1
		10	75.3/94.1	78.0/94.1	75.7/94.1	75.7/94.1	75.7/94.1
		30	82.2/97.0	83.9/97.9	82.7/98.7	83.5/98.6	82.2/98.4
		50	–	–	–	–	–
	50	5	75.3/94.1	78.4/94.1	76.2/94.1	76.1/94.1	76.9/94.1
		10	75.7/94.1	78.0/94.1	75.7/94.1	75.7/94.1	75.7/94.1
		30	86.8/ <b>102.0</b>	91.0/ <b>105.4</b>	86.9/ <b>102.1</b>	86.9/ <b>102.1</b>	86.9/ <b>102.1</b>
		50	90.6/ <b>107.5</b>	94.0/ <b>110.3</b>	90.5/ <b>107.6</b>	90.7/ <b>107.6</b>	90.7/ <b>107.6</b>
45	10	5	89.2/99.5	96.2/ <b>106.2</b>	89.6/99.8	89.1/99.2	89.2/99.2
		10	<b>116.1/133.6</b>	<b>120.4/137.7</b>	<b>115.7/133.1</b>	<b>115.4/132.6</b>	<b>115.5/132.9</b>
		30	–	–	–	–	–
		50	–	–	–	–	–
	50	5	93.9/ <b>105.3</b>	<b>100.6/111.5</b>	94.4/ <b>105.7</b>	94.2/ <b>105.1</b>	94.1/ <b>105.2</b>
		10	<b>110.6/126.5</b>	<b>117.1/132.7</b>	<b>111.0/127.0</b>	<b>111.1/126.9</b>	<b>111.1/127.0</b>
		30	<b>134.1/158.8</b>	<b>140.6/165.4</b>	<b>134.4/159.2</b>	<b>134.3/159.3</b>	<b>134.4/159.2</b>
		50	<b>142.8/171.5</b>	<b>148.8/178.4</b>	<b>143.0/172.4</b>	<b>142.9/171.8</b>	<b>143.0/171.9</b>

The degree of utilization ( $\Lambda$ ) values obtained in DA1 of Eurocode 7 (Table 6) are considered to be similar to those obtained in DA3 [1]. So, the calculations will also check this statement in specific design cases. Calculations were carried out for two combinations but only for cases characterized as less safe – more exposed to loss of stability, i.e. for slope inclination  $\alpha$  equaled to  $30^\circ$  and  $45^\circ$ . Using the Fellenius/Petterson method causes obtaining greater values of utilization degree ( $\Lambda$ ) in combination 1 (in stable cases) or in both combinations 1 and 2 (in unstable cases), but only for the case when  $\alpha = 45^\circ$ ,  $B = 10$  m, and  $H = 5$  m, the structure is assessed as unstable by the Fellenius/Petterson method and stable by other methods. The calculations done for combination 2 are estimated more rigorous; they are stable for slope inclination  $\alpha = 30^\circ$ , waste width  $B = 10$  m and its height  $H = 5$ – $50$  m, as well as  $\alpha = 45^\circ$ ,  $B = 10$  m and  $H = 5$  m. In the case of combination 1, the structure is stable when:  $\alpha = 30^\circ$ , waste width  $B = 10$  and  $50$  m, and its height  $H = 5$ – $50$  m, as well as  $\alpha = 45^\circ$ ,  $B = 10$  m and  $H = 5$  m.

The calculations according to DA1 give the same results regardless of the method of checking the stability only in the case of combination 2 and the slope inclination  $\alpha = 30^\circ$ , the waste width  $B$  equal to 10 and 50 m, and the storage height  $H = 5$ – $10$  m.

The calculation results according to DA3 and combination 2 of DA1 (material properties) are the same. In some cases, only slight differences down to decimal places of the degree of utilization ( $\Lambda$ ) are observed, which is a problem of calculation accuracy.

Table 7 shows, for comparison, the results obtained when calculating the safety factor.

Table 7. The factor of safety  $F$  ( ) in dependence on slope geometry and calculation method

Geometry of the waste body			The factor of safety $F$ (–) for method				
$\alpha$ (°)	$B$ (m)	$H$ (m)	Bishop	Fellenius/ Petterson	Spencer	Janbu	Morgenstern- Price
20	10	5	1.33				
		10					
		30					
		50	1.73	1.71	1.75	1.75	1.75
	50	5	1.33				
		10					
		30					
		50	1.77	1.73	1.76	1.76	1.76
25	10	5	1.33				
		10					
		30					
		50	1.42	1.40	1.43	1.43	1.43
	50	5	1.33				
		10					
		30					
		50	1.41	1.38	1.41	1.41	1.41

Table continued on the next page

Table continued from the previous page

Geometry of the waste body			The factor of safety $F$ (–) for method				
$\alpha$ (°)	$B$ (m)	$H$ (m)	Bishop	Fellenius/ Pettersen	Spencer	Janbu	Morgenstern- Price
30	10	5	1.33				
		10	1.33				
		30	1.29	1.28	1.27	1.27	1.27
		50	–	–	–	–	–
	50	5	1.33				
		10	1.33				
		30	1.22	<b>1.19</b>	1.22	1.22	1.22
		50	<b>1.16</b>	<b>1.13</b>	<b>1.16</b>	<b>1.16</b>	<b>1.16</b>
45	10	5	1.26	<b>1.18</b>	1.25	1.25	1.26
		10	<b>0.94</b>	<b>0.91</b>	<b>0.94</b>	<b>0.94</b>	<b>0.94</b>
		30	–	–	–	–	–
		50	–	–	–	–	–
	50	5	<b>1.19</b>	<b>1.13</b>	<b>1.18</b>	<b>1.18</b>	<b>1.19</b>
		10	<b>0.99</b>	<b>0.94</b>	<b>0.98</b>	<b>0.98</b>	<b>0.98</b>
		30	<b>0.79</b>	<b>0.76</b>	<b>0.79</b>	<b>0.78</b>	<b>0.79</b>
		50	<b>0.73</b>	<b>0.70</b>	<b>0.72</b>	<b>0.73</b>	<b>0.73</b>

Calculations of the waste landfill stability considering the safety factor (Table 7) practically reproduced results obtained under DA3 of Eurocode 7 [2]. They may be more or less rigorous, depending on the accepted value of the stability factor. Considering the safety factor should be  $F_p = 1.2$ – $1.3$  [26, 28], structures with the waste body slope  $\alpha = 45^\circ$  and waste width  $B = 50$  m can be estimated as unstable, though waste with  $B = 10$  m for the height of 5 m is stable. The slopes with an inclination of  $\alpha = 30^\circ$ , waste width  $B = 50$  m and height  $H = 50$  m are unstable too. Analysing DA3 almost the same results of stability calculations have been obtained. Assuming the  $F_p \geq 1.3$  [1], the stability condition is met only by the structure with an inclination of  $\alpha = 20^\circ$  and  $25^\circ$  and all width and height of the waste body. Slopes with a greater inclination  $\alpha = 30^\circ$  meet the condition stability if the height of the stored waste is 10 m or less.

In the case of all DAs for the applied landfill geometry, the most unfavourable slip surfaces occurred:

- in the drainage layer placed on the slope of the landfill when  $\alpha = 20$ – $25^\circ$  for all calculation cases and when  $\alpha = 30^\circ$ ,  $B = 10$  m, and  $B = 50$  m (with  $H = 5$  and 10 m);
- in the waste body when  $\alpha = 30^\circ$ ,  $B = 50$  m (with  $H = 30$  and 50 m), and all calculation cases when  $\alpha = 45^\circ$ .

As in calculations according to DAs of Eurocode 7, slightly lower values of the factors of safety  $F$  were achieved by the Fellenius/Petterson method. Only in two cases structures is assessed as unstable by the Fellenius/Petterson method and stable by other methods. Earlier literature items denoted much lower  $F$  values in the case of the Fellenius method compared to other methods than those obtained for the municipal waste lined with a mixed sealing system.

## 5. Conclusions

1. Verification of the stability of the municipal waste landfill lined with a complex sealing, following three approaches of Eurocode 7, showed the similarity of DA3, approved by the Polish National Annex, and accepted in most CEN countries, with combination 2 of DA1, where the primary variable is the material properties. The use of DA2 specifies lower values of the degree of utilization than DA3 or DA1 (combination 2) for the same cases, so the approach is less stringent, which is different from what was demonstrated by [1].
2. Calculations considering the values of safety factors, i.e., using characteristic values of parameters and actions, showed similarity in slope stability results to an estimation of slope stability using DA3, but only when the acceptable value of the stability factor is in the range of 1.2–1.3. If the adopted minimum value of the safety factor is higher, the analysis will be much more stringent than in the case of DAs of Eurocode 7.
3. It should be emphasized that the calculation procedures using safety factors, based on the characteristic values of parameters and actions, and DA3 of EC7 with partial factors and degree of utilization are different, but the stability assessment results are similar.
4. In the applied calculation cases, the location of the most unfavourable slip surface is influenced primarily by the inclination of the waste slope, and next by waste body height and width.
5. The use of the Fellenius/Petterson method leads to an underestimation of the safety factor or an overstatement of the degree of utilization, thus an incorrect assessment of the structure's safety, which is widely known. Other methods of assessing structure stability – the Bishop, Janbu, or Morgenstern–Price methods provide the same or comparable results.

## References

- [1] A. Bond and A. Harris, *Decoding Eurocode 7*. London: CRC Press, 2008.
- [2] EN 1997-1:2004 Eurocode 7: Geotechnical design – Part 1. European Committee for Standardization, 2004.
- [3] Y. Huang and G. Fan, “Engineering geological analysis of municipal solid waste landfill stability”, *Natural Hazards*, vol. 84, no. 1, pp. 93–107, 2016, doi: [10.1007/s11069-016-2408-8](https://doi.org/10.1007/s11069-016-2408-8).
- [4] B. Gharabaghi, M.K. Singh, C. Inkratas, I.R. Fleming, and E. McBean, “Comparison of slope stability in two Brazilian municipal landfills”, *Waste Management*, vol. 28, no. 9, pp. 1509–1517, 2007, doi: [10.1016/j.wasman.2007.07.006](https://doi.org/10.1016/j.wasman.2007.07.006).
- [5] R.J. Kelly, B.D. Shearer, J. Kim, C.D. Goldsmith, G.R. Hater, and J.T. Novak, “Relationships between analytical methods utilized as tools in the evaluation of landfill waste stability”, *Waste Management*, vol. 26, pp. 1349–1356, 2006, doi: [10.1016/j.wasman.2005.11.019](https://doi.org/10.1016/j.wasman.2005.11.019).
- [6] B. Zadroga and K. Olańczuk-Neyman, *Protection and reclamation of the subsoil. Geotechnical and construction aspects*. Gdańsk, Poland: Oficyna Wydawnicza Politechniki Gdańskiej, 2001 (in Polish).
- [7] C.A. Bareither, C.H. Benson and T.B. Edil, “Effects of waste composition and decomposition on the shear strength of municipal solid waste”, *Journal of Geotechnical and Geoenvironmental Engineering*, vol. 138, no. 10, pp. 1161–1174, 2012, doi: [10.1061/\(ASCE\)GT.1943-5606.0000702](https://doi.org/10.1061/(ASCE)GT.1943-5606.0000702).

- [8] C.C. Gomes and M.L.C. Lopes, "Characterisation of municipal solid waste physical properties and their evolution with age", *Geotechnical Engineering*, vol. 165, no. 1, pp. 12–34, 2012, doi: [10.1680/geng.10.00016](https://doi.org/10.1680/geng.10.00016).
- [9] T. Zydroń, M. Cholewa, and P. Demczuk, "Shear strength of municipal waste and stability of structure slopes", *Acta Scientiarum Polonorum Formatio Circumiectus*, vol. 14, no. 4, pp. 141–155, 2015, doi: [10.15576/ASP.FC/2015.14.4.141](https://doi.org/10.15576/ASP.FC/2015.14.4.141) (in Polish).
- [10] N. Dixon and D.R.V. Jones, "Engineering properties of municipal solid waste", *Geotextiles and Geomembranes*, vol. 23, no. 3, pp. 205–233, 2005, doi: [10.1016/j.geotexmem.2004.11.002](https://doi.org/10.1016/j.geotexmem.2004.11.002).
- [11] M.A. Gabr, M.S. Hossain, and M.A. Barlaz, "Shear strength parameters of municipal solid waste with leachate recirculation", *Journal of Geotechnical and Geoenvironmental Engineering*, vol. 133, no. 4, pp. 478–484, 2007, doi: [10.1061/\(ASCE\)1090-0241\(2007\)133:4\(478\)](https://doi.org/10.1061/(ASCE)1090-0241(2007)133:4(478)).
- [12] D. Zekkos, et al., "Unit weight of municipal solid waste", *Journal of Geotechnical and Geoenvironmental Engineering*, vol. 132, no. 10, pp. 1250–1261, 2006, doi: [10.1061/\(ASCE\)1090-0241\(2006\)132:10\(1250\)](https://doi.org/10.1061/(ASCE)1090-0241(2006)132:10(1250)).
- [13] A.S.S. Raghuram, P.S. Negi, B.M. Basha, and A.A.B. Moghal, "Effect of sample size, dry unit weight, and hysteresis of expansive soil on SWCC and finite slope stability", *International Journal of Geosynthetics and Ground Engineering*, vol. 10, no. 2, art. no. 18, 2024, doi: [10.1007/s40891-024-00531-9](https://doi.org/10.1007/s40891-024-00531-9).
- [14] A. Bouazza and W.F. Van Impe, "Liner design for waste disposal sites", *Environmental Geology*, vol. 35, no. 1, pp. 41–54, 1998, doi: [10.1007/s002540050291](https://doi.org/10.1007/s002540050291).
- [15] D.E. Daniel, Ed. *Geotechnical practice for waste disposal*. London, UK: Chapman & Hall, 1997.
- [16] B. Łuczak-Wilamowska, "Geological conditions of storage of municipal waste", *Biuletyn Państwowego Instytutu Geologicznego*, vol. 455, pp. 1–142, 2013 (in Polish).
- [17] R.K. Rowe, R.M. Quigley, R.W.I. Brachman, and J.R. Booker, *Barrier systems for waste disposal facilities*. London, UK: CRC Press, 2004.
- [18] Council Directive 1999/31/EC of 26 April 1999 on the landfill of waste. Official Journal of the European Union 182, 16.7.1999, pp. 1–19.
- [19] H. Haddad, B. Fatahi, H. Khabbaz, J. Hsi and I. Li, "Effects of stress history on compressibility characteristics of undisturbed landfill waste material", *Construction and Building Materials*, vol. 422, art. no. 135725, 2024, doi: [10.1016/j.conbuildmat.2024.135725](https://doi.org/10.1016/j.conbuildmat.2024.135725).
- [20] K. Zabielska-Adamska, *Anthropogenic soils. Compactability and properties of compacted soils*. Warsaw, Poland: KILiW PAN, 2019 (in Polish).
- [21] X. Qian and R.M. Koerner, "Critical interfaces and waste placement in landfill design", *Environmental Geotechnics*, vol. 4, no. 3, pp. 160–170, 2017, doi: [10.1680/envgeo.14.00018](https://doi.org/10.1680/envgeo.14.00018).
- [22] T.D. Stark and A.R. Poeppel, "Landfill liner interface strengths from torsional–ring–shear tests", *Journal of Geotechnical Engineering*, vol. 120, no. 3, pp. 597–615, 1994, doi: [10.1061/\(ASCE\)0733-9410\(1994\)120:3\(597\)](https://doi.org/10.1061/(ASCE)0733-9410(1994)120:3(597)).
- [23] K. Zabielska-Adamska, "Shear strength parameters of compacted fly ash–HDPE geomembrane interfaces", *Geotextiles and Geomembranes*, vol. 24, no. 2, pp. 91–102, 2006, doi: [10.1016/j.geotexmem.2005.11.006](https://doi.org/10.1016/j.geotexmem.2005.11.006).
- [24] J. Sulewska, "Stability of the waste landfill structure", MSc thesis, Białystok University of Technology, Poland, 2019 (in Polish).
- [25] K. Zabielska-Adamska and J. Markowska, "Stability of stored municipal waste for different sealing system", *Architecture, Civil Engineering, Environment*, vol. 16, no. 4, pp. 125–133, 2023, doi: [10.2478/acee-2023-0056](https://doi.org/10.2478/acee-2023-0056).
- [26] E. Koda, "Landfills. Stability of municipal landfill slopes", in *XXIV Ogólnopolskie Warsztaty Pracy Projektanta Konstrukcji*. Wisła, Poland: Dolnośląska Okręgowa Izba Inżynierów Budownictwa, 2009, pp. 13–49 (in Polish).
- [27] E. Koda, M. Grzyb, P. Osiniński, and M.D. Vaverkova, "Analysis of failure in landfill construction elements", *MATEC Web of Conferences*, vol. 284, no. 03002, 2019, doi: [10.1051/mateconf/201928403002](https://doi.org/10.1051/mateconf/201928403002).
- [28] E. Koda, A. Kiersnowska, J. Kawalec, and P. Osiniński, "Landfill slope stability improvement incorporating reinforcements in reclamation process applying observational method", *Applied Sciences*, vol. 10, no. 5, art. no. 1572, 2020, doi: [10.3390/app10051572](https://doi.org/10.3390/app10051572).
- [29] M.S. Hossain and M.A. Haque, "Stability analyses of municipal solid waste landfills with decomposition", *Geotechnical and Geological Engineering*, vol. 27, no. 6, pp. 659–666, doi: [10.1007/s10706-009-9265-0](https://doi.org/10.1007/s10706-009-9265-0).
- [30] European Technical Committee No. 8 (ETC 8), *Geotechnics of landfill design and remedial works – Technical recommendation GLR*. Berlin, Germany: Ernst & Sohn, 1993.

## Wpływ metody obliczeń na wyniki analizy stateczności składowanych odpadów komunalnych

**Słowa kluczowe:** analiza stateczności skarp, mieszane uszczelnienia składowisk, obliczenia stateczności składowanych odpadów, podejścia obliczeniowe Eurokodu, składowanie odpadów komunalnych

### Streszczenie:

W pracy przedstawiono analizy stateczności odpadów komunalnych składowanych na składowisku podścielonym warstwą drenażową i mieszaną warstwą uszczelniającą. Warstwę drenażową stanowi piasek średni w stanie zagęszczonym, natomiast mieszaną warstwę uszczelniającą buduje zagęszczona glina zwięzła oraz geosyntetyczna bariera w postaci dwustronnie teksturowanej geomembrany PEHD. Pod uszczelnieniem znajduje się geowłóknina o funkcji drenażowej i ochronnej. Składowisko przyjęto jako podpoziomowe w wykopie, gdzie maksymalna wysokość składowania odpadów jest równa wysokości skarpy wykopu. Założono zmienne parametry geometryczne masywu odpadów komunalnych, takie jak wysokość, szerokość korony masywu oraz jego nachylenie. Analizę stateczności konstrukcji wykonano z wykorzystaniem programu numerycznego GEO5 (moduł Slope Stability), uwzględniając metody równowagi granicznej: Felleniusa/Pettersona, Bishopa, Spencera, Janbu i Morgensterna-Price'a, przy założeniu kołowej powierzchni poślizgu. Rozważania przeprowadzono zgodnie z podejściem 3 (DA3) Eurokodu 7 według polskiego załącznika krajowego i akceptowanego w większości krajów CEN oraz według podejść 1 (DA1) i 2 (DA2) przyjętych w innych krajach CEN. Podano wartości stopnia wykorzystania (współczynnika wykorzystania) dla stanu granicznego nośności GEO według Eurokodu 7. Obliczenia stateczności wykonano także z uwzględnieniem wartości współczynników bezpieczeństwa, tj. wykorzystując charakterystyczne wartości parametrów i oddziaływań. Porównano wartości współczynników wykorzystania uzyskanych we wszystkich podejściach projektowych oraz współczynniki bezpieczeństwa.

Received: 2024-09-02, Revised: 2024-11-05