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Municipal waste management based on geomechanical assessments of the landfill site slope – a case study in southern Poland

Author(s) ORCID Identifier:
Tomasz Janoszek: 0000-0001-7006-0285
Phu Minh Vuong Nguyen: 0000-0002-4895-8811
Jacek Grabowski: 0000-0002-4215-4505

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Abstract

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This paper presents an attempt to determine the available area of a landfill where municipal waste can be safely deposited for further operation. For this purpose, a numerical slope stability analysis was carried out using the finite difference method code FLAC3D, presenting the actual geomechanical conditions of a landfill located in southern Poland. Based on the numerical results, options for municipal waste storage were presented and discussed. The proposed design chart aims to help landfill owners/managers make an adequate decision in terms of landfill planning and design.

Keywords

slope stability analysis, shear strength, municipal waste, numerical modelling

Municipal waste management based on geomechanical assessments of the landfill site slope – A case study in southern Poland

Tomasz Janoszek [a], Phu Minh Vuong Nguyen [a,*], Jacek Grabowski [b]

[a] Central Mining Institute – National Research Institute, Department of Extraction Technologies, Rockburst and Risk Assessment, Poland
[b] Central Mining Institute – National Research Institute, Department of Environmental Monitoring, Poland

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Over time, municipal waste landfills tend to go higher and become larger. The stability of the municipal landfill slope is one of the basic geotechnical tasks. This task ensures continuous waste deposition on the landfill surface and safety in its surroundings. With the increasing height and volume of the landfill, it is difficult to estimate the available area of the municipal landfill, where more waste can be safely deposited due to a number of variable factors, such as the geotechnical conditions of the municipal landfill, the morphological composition, age, and degree of compaction and decomposition of the deposited waste.

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1. Introduction

Waste management constitutes one of the most neglected environmental protection areas. Wastes are frequently disposed in a manner that does not protect the environment and people against their negative impact; they cause the degradation of the earth's surface and pollute underground and surface waters as well as the air [1–4]. Changes in waste management took place in the twenty-first century, including at the time of Poland's accession to the EU [5–7]. Significant changes included reducing the negative impact of landfills, including municipal waste, on the environment and human health, as well as changes in technical equipment and rules for the operation of landfills [8,9].

Volume and morphology of the municipal waste landfill are significantly influenced by the region in which it is located, particularly by the level of societal affluence and the consequent level of product consumption, but also by the time of year. The amount of municipal rubbish collected per person annually and the state of the economy in each region of the nation are highly associated. The type and quantity of waste collected also depend on the location of a landfill (urban or rural area), the population density, the type of householders (single-family or multi-family), the number of yearly visited tourists, the presence of public buildings and the type, size, and number of malls, shops as well as any small businesses or services [8,10,11].

During the operation of high-level municipal waste facilities, a major challenge, apart from

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* Corresponding author.
E-mail address: pnguyen@gig.eu (P.M.V. Nguyen).

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ensuring the protection of the water and soil environment, is to maintain the required stability of slopes and hillsides. Due to progressing limitations in the availability of useable storage areas during operation, municipal waste is being disposed of at ever greater heights. It is necessary to maintain the slope walls of the waste body stable. The loss of slope stability at the landfill sites may lead to the occurrence of landslides [12−18] and, consequently, to the expansion of waste material towards the adjacent land, disturbing its integral environmental values and even to human and property loss [19−21].

According to the Polish National Waste Management Plan 2022 [22], at the end of 2014, the overall number of municipal waste landfill sites for non-hazardous and non-inert waste, excluding abandoned landfills, reached 417 installations. The average volume of municipal waste deposited in Poland over the past ten years is shown in Figures 1 and 2. According to a study of the statistics, there are currently 63.7 million Mg (79.7 million m^3) of landfill capacity available for non-hazardous and non-inert waste that meets the requirements. This means it will be sufficient to deposit the current weight of municipal waste for the next 11 years, till 2025.

The basic components of waste disposal of landfill sites are plastics, paper, glass, textiles, metals, vegetable and animal waste and a slight content of inorganic waste. Due to the fact that municipal landfill sites are a mixture of many biodegradable components over time, it is a significant issue to assess correctly the geotechnical parameters of municipal waste [23−30]. This problem concerns mainly long-term municipal landfill sites that have been operated for more than ten years, with a slope height of more than 50 m, and the slope inclination often exceeds the ratio of 1:1 [31−33]. Lack of proper assessments of the landfill slope stability can lead to slope failure on one side while limiting the landfill's capacity on the other side.

The paper presents an attempt to determine the available area for future deposition of an actual municipal landfill site based on the numerical modelling results. The surface geometry of the solid waste under investigation was identified based on geodetic measurements (point clouds) of the currently operated landfill area. Based on the developed 3D model of the municipal landfill body, a numerical analysis of slope stability was carried out by determining the factor of safety (FoS) by the shear strength reduction technique (SRM) taking variable parameters of the solid waste into consideration: cohesion and angle of internal friction. Possible failure surfaces of a municipal landfill in the paper are defined as unusable, while stable surfaces are defined as useable surfaces where solid waste can be placed. As a result, the proposed design chart is expected to assist waste management in decision-making.

2. Characteristics of the studied site

2.1. Location of the studied site

The investigated object is a municipal landfill site with a total area of about 13 ha (130,000 m^2) located in southern Poland (Fig. 3). On the western side, it borders on the old reclaimed landfill exploited in 1987−1994 with a wooded protective zone. From the east and south sides, it is surrounded by forest, and

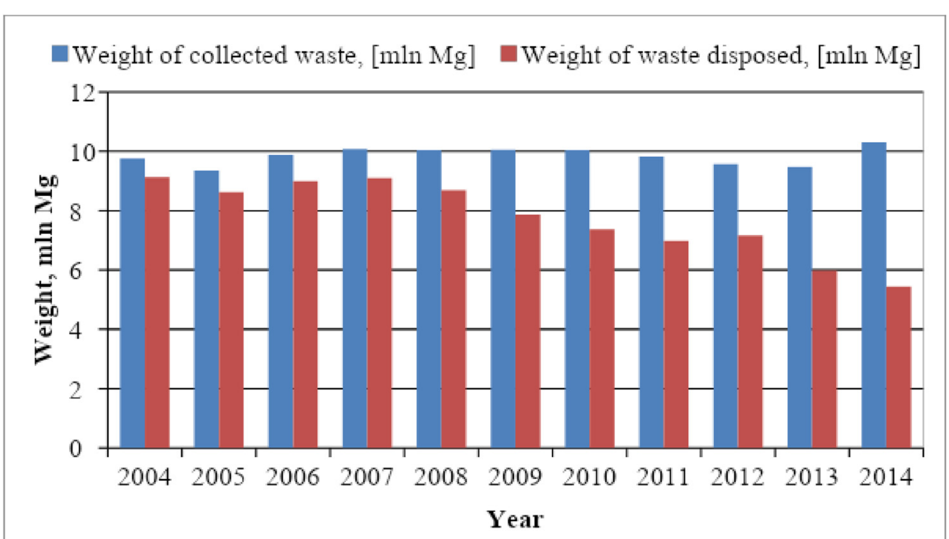

Fig. 1. Total disposed municipal waste in the period of 2004−2014, Poland [22].

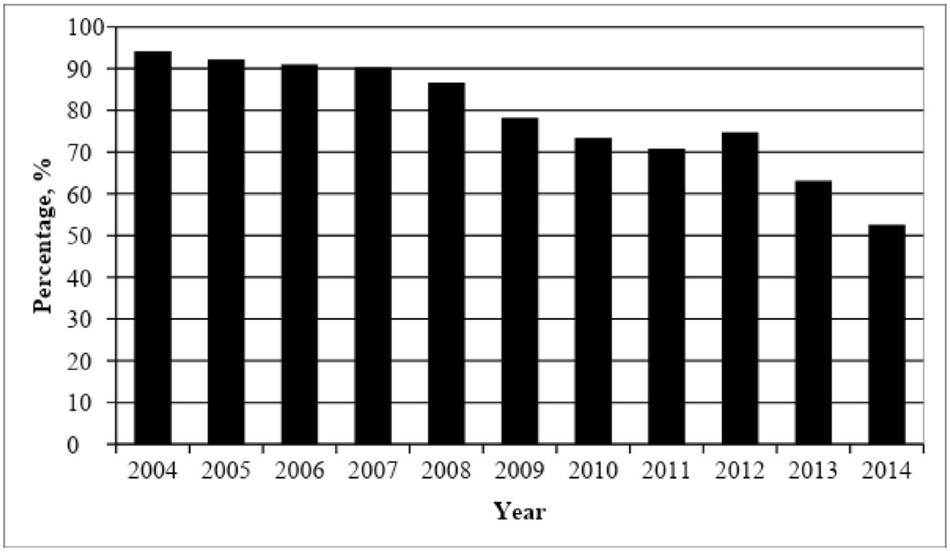

Fig. 2. Percentage of waste disposed in the period of 2004–2014, Poland [22].

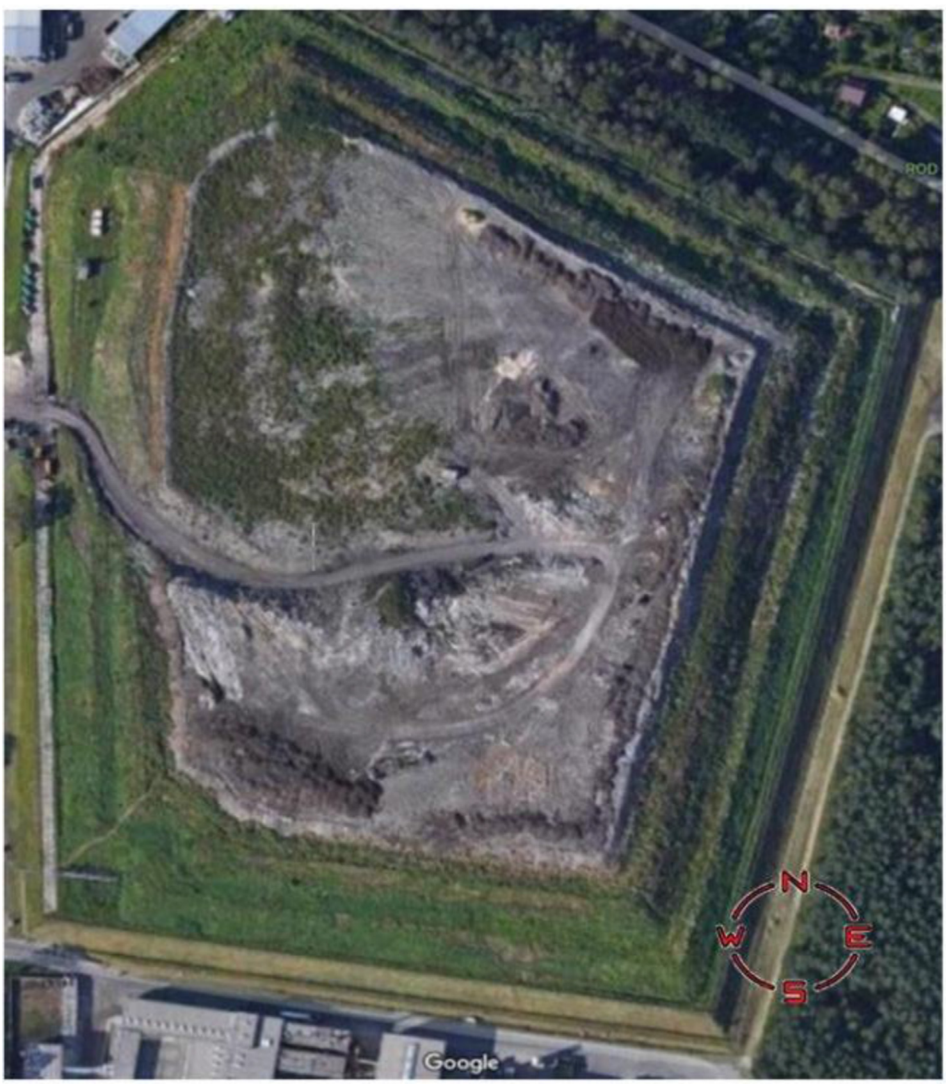

Fig. 3. The top view of the municipal landfill site.

from the north, it adjoins the railroad line. It is a facility that meets all the requirements of environmental protection [34]. In 2004, the landfill was expanded with a new section with an area of 8.5 ha, thus reaching a capacity of approx. 1,500,000 m^3 [35].

2.2. Geotechnical characteristics of studied site

The municipal landfill site consists of three quarters. The first section, with a surface area of 3.5 ha, was created on the area of the sand pit. Initially, it functioned as a construction waste dump, but since 1988, municipal waste has been deposited. In 1994 the site was closed. The reason was the lack of any protection against leachate entering the groundwater. Two years later, reclamation work began by covering the top with high-density polyethylene (HDPE) plastic sheeting. Next, the HDPE plastic sheeting was covered with an average layer of soil 50 cm thick. The reclamation did not result in a significant improvement in water quality [36−40].

Subsoil consists of alluvial soils, sands and gravels of accumulation terraces. These formations are covered by glacial and fluvial deposits represented by sands, gravels and clays. The thickness of the Quaternary sediments mentioned does not exceed 20 m. There are Tertiary clays and silty clays below. Their thickness varies and may exceed 150 m. In the area of the landfill site, Triassic limestones and the underlying Carboniferous sandstones and conglomerates are exposed locally [40,41]. An example of a map of geotechnical soil layers is presented in Figure 4. Geotechnical parameters characterising individual samples of the Quaternary sediments are summarised in Table 1.

2.3. Hydrogeological conditions

At the studied municipal landfill site, there are distinguishing Quaternary, locally Triassic and Carboniferous aquifers. The Quaternary aquifer is formed by sands, and in the southern part also by gravels, creating one aquifer. Locally, this aquifer is separated by clayey formations. Water flows under the landfill from north to south. The main source of groundwater is infiltration from precipitation. The groundwater aquifer in the area of the analysed municipal landfill is monitored by 18 piezometers. According to the research carried out, the first groundwater table above the ground surface was drilled at a depth of 3.0−4.5 m below ground level. It characterises a relaxed or slightly localised tension.

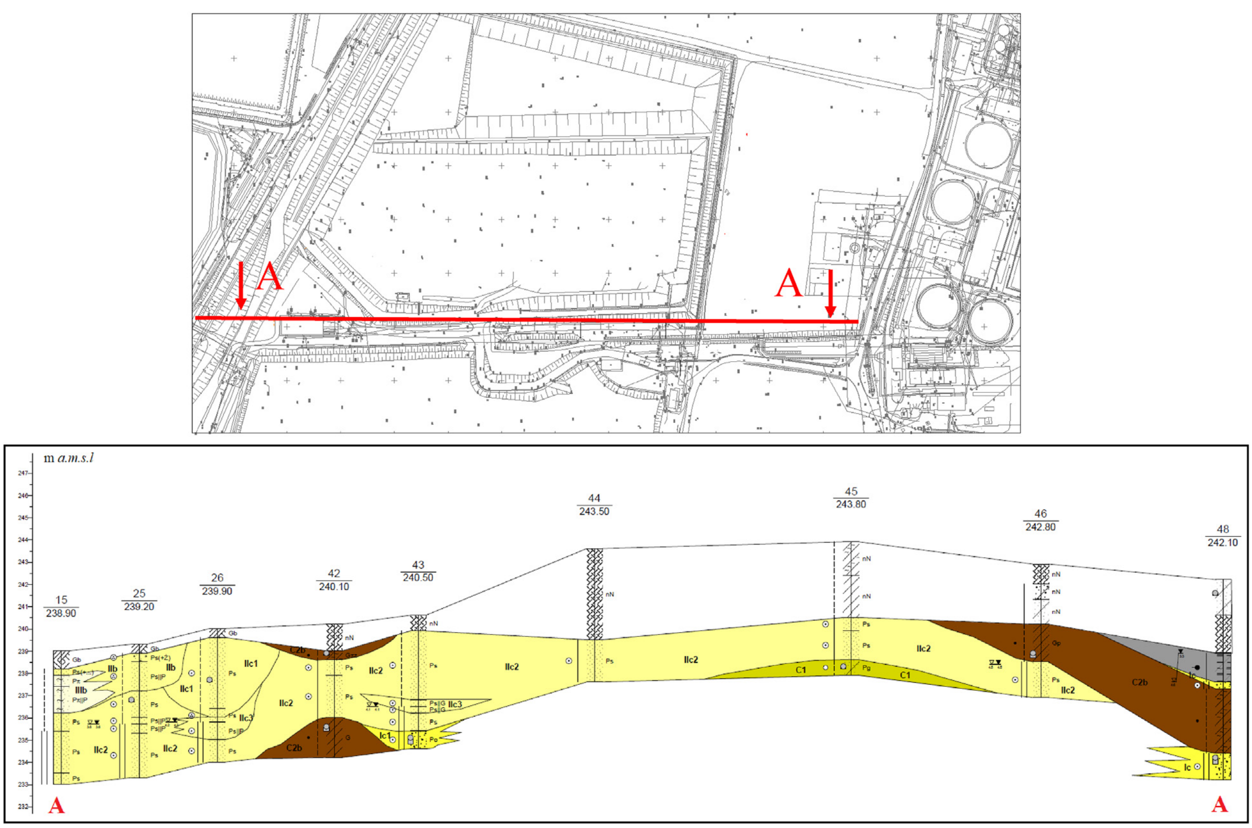

Fig. 4. An example of geological cross-section at the studied site [38,41,42].

Table 1. Geotechnical parameters of subsoil layers [38,41,42].

Layer symbol	Type of soil	Degree of compaction of non-cohesive soil	Degree of compaction of cohesive soil	Cohesion, kPa	Friction angle, °	Young's modulus, MPa	Compressibility modulus, MPa	Density, Mg/m^3
Ic	Condensed alluvium	0.50	–	–	38	140	155	1.75–2.05
IIb	Strong compacted sands	0.70	–	–	34	110	130	1.80–2.05
IIc1	Medium compacted sands	0.65	–	–	34	100	120	1.70–2.00
IIc2	Medium compacted sands	0.60	–	–	33	95	110	1.70–2.00
IIc3	sands	0.5	–	–	33	80	100	1.70–2.00
IIIb	Strong compacted silty sands	0.7	–	–	31	65	85	1.70–2.00
IIIc	Medium compacted silty sands	0.5	–	–	30	50	65	1.65–1.90
C1	Semi-compact clayey sands	–	0.0	30	18	34	58	2.20
C2a	Hard-plastic Sandy clays/silty clays	–	0.1	20	16	25	36	2.10–2.20
C2b	Clays/silty clays	–	0.2	16	15	20	30	2.00–2.15
C4	Soft-plastic clayey sands	–	0.6	8	8	10	12	2.05

Water is found within the sandy layers. The tension layers are silty and clayey interlayers. The water permeability of medium sands determined on the basis of laboratory tests ranges from 21.77 m per day to 77.50 m per day. For silty sands, the water permeability *ranges* from 0.57 m per day to 0.39 m per day [36,37,43,44].

3. Material and methods

The numerical calculations were performed in FLAC3D (Fast Lagrangian Analysis of Continua). FLAC3D is a program based on the finite difference method intended to perform numerical analyses of the mechanical behaviour of structures made of soil, rock, or other geomaterials and their interactions. FLAC/FLAC3D was applied for a number of slope stability analysis cases [45–52].

3.1. Model geometry

The model geometry of the analysed municipal waste landfill site was mapped in three stages. The first stage consisted of digitising the shape of the municipal landfill. The result was a point cloud that allowed mapping the geometry and dimensions of the reconstructed object, as shown in Figure 5a. The second stage involved the process of mapping the model of the surface. Obtaining the shape model of the municipal landfill surface required transforming the geodetic data in three successive phases: points, polygons and surfaces (Fig. 5b). The next step was the preparation of the measurement point in the form of a cloud, which included noise clustering, correction, defect infraction, and uniformization. The properly processed point cloud was transformed into a surface model in STL (stereolithography) format created from a triangular mesh, and the results are presented in Figure 5c.

The final step of the municipal landfill geometry modelling process was to convert the STL (stereolithography) surface model into a solid model. The results are presented in Figure 6.

A model of the municipal landfill site with a height of approx. 50 m, a width of 420 m, and a length of 210 m was developed.

3.2. Numerical grid

The numerical model of the municipal landfill presents a volume of the solid body, which is divided into 812,500 quadrilateral elements (standard FLAC3D brick mesh shape) (Fig. 7).

The brick mesh shape can be interpreted in Figure 8.

3.3. Assumptions

The study of the stability of the municipal landfill was based on the Mohr-Coulomb strength criterion, according to the relationship:

$$|\tau| = \sigma tg\varphi + c \quad (1)$$

Mohr-Coulomb model is often chosen due to its availability in computer programs, its simplicity and

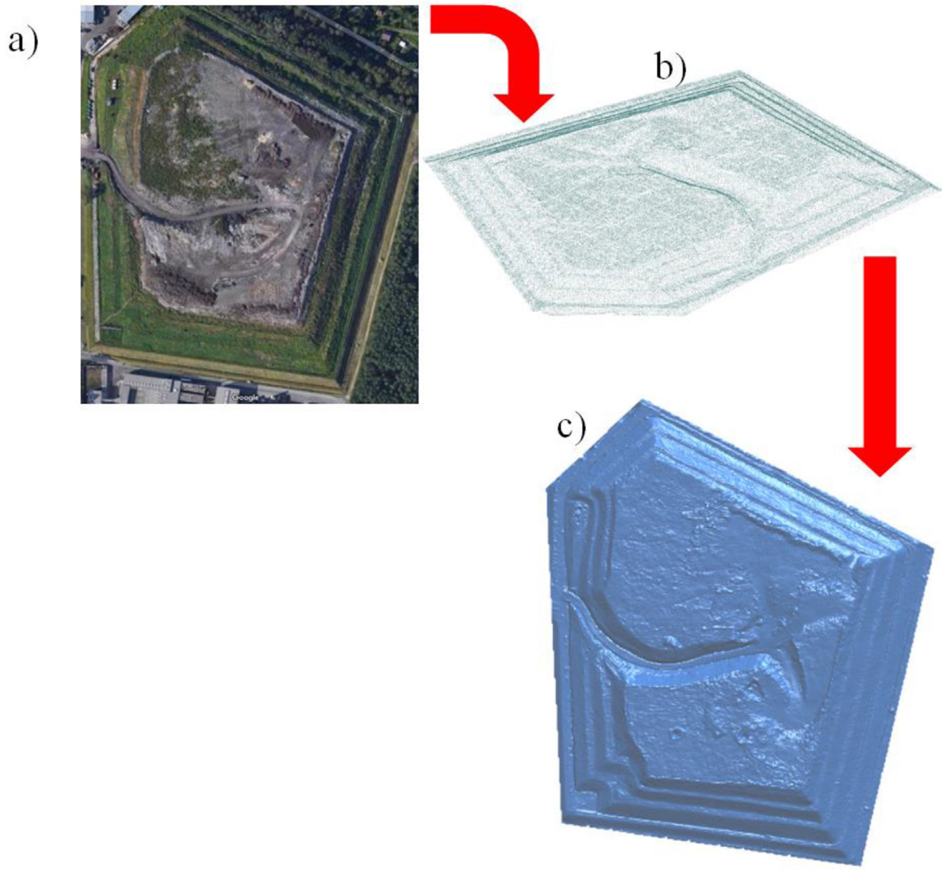

Fig. 5. Stages of municipal landfill model reconstruction: a — real view of municipal landfill, b — point cloud of municipal landfill surface, c — stereolithographic model of municipal landfill surface.

good understanding. At present, this constitutive model is still very common in practice to simulate soil behaviour. The Mohr-Coulomb model was used for numerical modelling of the issue of the interaction between a municipal landfill and the soil layer. Assuming Mohr-Coulomb constitutive model for the subsoil and the municipal landfill waste requires the following parameters:

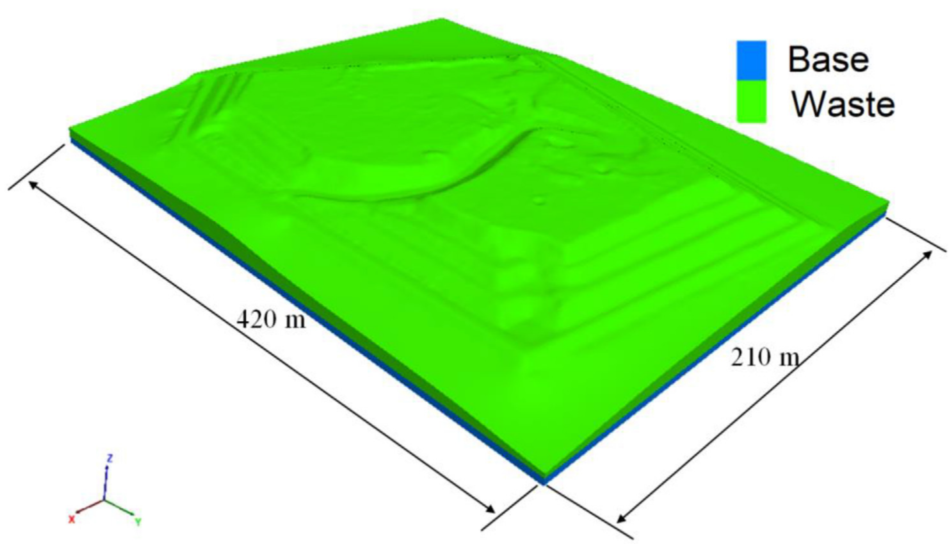

Fig. 6. 3D model of the studied municipal landfill site.

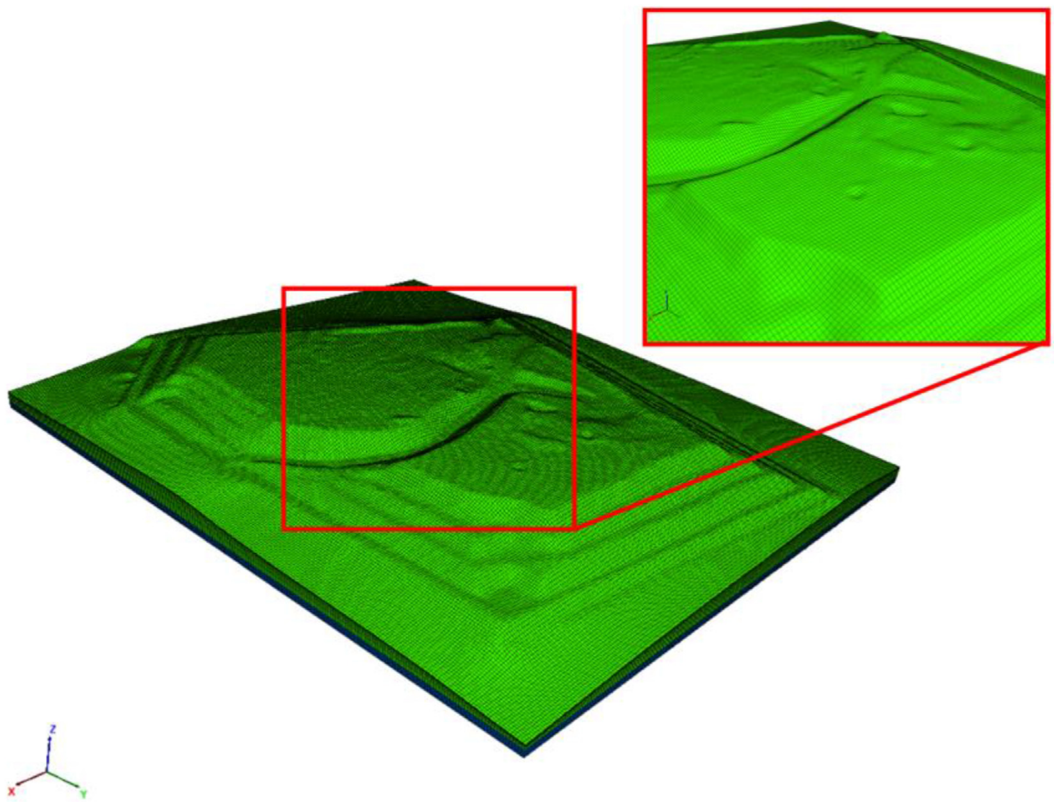

Fig. 7. Numerical grid of the studied municipal landfill.

– shear modulus G and bulk modulus K

$$G = \frac{E}{2(1+v)} \tag{2}$$

$$K = \frac{E}{3(1-2v)} \tag{3}$$

or Young's modulus E and Poisson's ratio v

$$E = \frac{9KG}{3K+G} \tag{4}$$

$$v = \frac{3K-2G}{2(3K+G)} \tag{5}$$

– friction angle φ,
– cohesion c.

The strength reduction method (SRM) was used to calculate a factor of safety (FoS) as a material failure

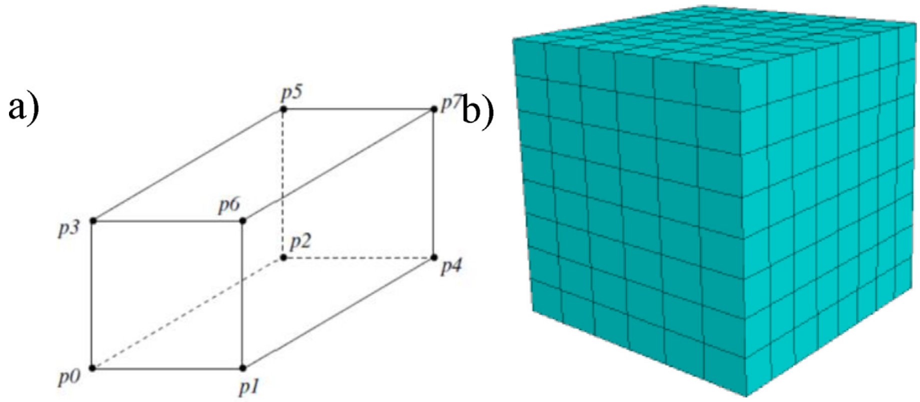

Fig. 8. The standard FLAC3D brick mesh shape: a — corner coordinate keywords, b — zone volumes [48].

model criteria based on the reduction of a strength property. The SRM has been implemented in the numerical model in aspects of the Mohr-Coulomb model failure criterion and the simultaneous reduction of strength properties: cohesion *(c)* and angle of internal frictional (φ). Both parameters are reduced by a series of simulations using trial values of the factor F_{trial} until slope failure occurs. In this case, the safety factor F is defined according to the equations [48]:

$$c^{trial} = \frac{1}{F^{trial}} c \quad (6)$$

$$\varphi^{trial} = \arctan\left(\frac{1}{F^{trial}} \tan\varphi\right) \quad (7)$$

3.4. Mechanical properties of municipal waste

Municipal waste is characterised by diverse and heterogeneous waste material in terms of morphology and its state of compaction. The shear strength parameters depend on many factors, such as age, composition, and moisture content of the municipal waste. For example, as a result of waste decomposition, the value of the internal friction angle tends to decrease. Because of this, it is difficult to determine the parameters of the shear strength of municipal waste. Based on the available data, the municipal wastes can be characterised by the high variability of internal friction angle and cohesion values: the angle of internal friction (ø) is in a range from 15° to 45°, while cohesion *(c)* is up to 50 kPa [13,15,24,28,53–59]. A precise determination of the quantity and the geotechnical properties of deposited waste is crucial for assessing the stability of landfill slopes and designing reinforcing measures if necessary. Hence, the geotechnical characteristics of each landfill site should be determined individually.

Figures 9 and 10 present the variability of the shear strength of municipal waste at the studied landfill site. In the case of friction angle, a high probability (87.5% of total measurements) of value is found in a range of 22–42°, while in the case of cohesion, the majority of value (ok. 83% of total measurements) is less than 25 kPa.

3.5. Calculation variations

Due to the high variability of the angle of internal friction and cohesion of waste materials, an analysis of landfill slope stability was carried out for various values of shear strength with the actual geometry of the municipal landfill site. Three major calculation variants were considered:

- Variation I – analysis of the stability of the municipal landfill for a constant value of the parameter of the angle of internal friction equal to 15° and a variable value of cohesion in the range from 0 to 50 kPa,
- Variation II – analysis of the stability of the municipal landfill for a constant value of the angle of internal friction equal to 30° and for a variable value of cohesion in the range from 0 to 50 kPa,

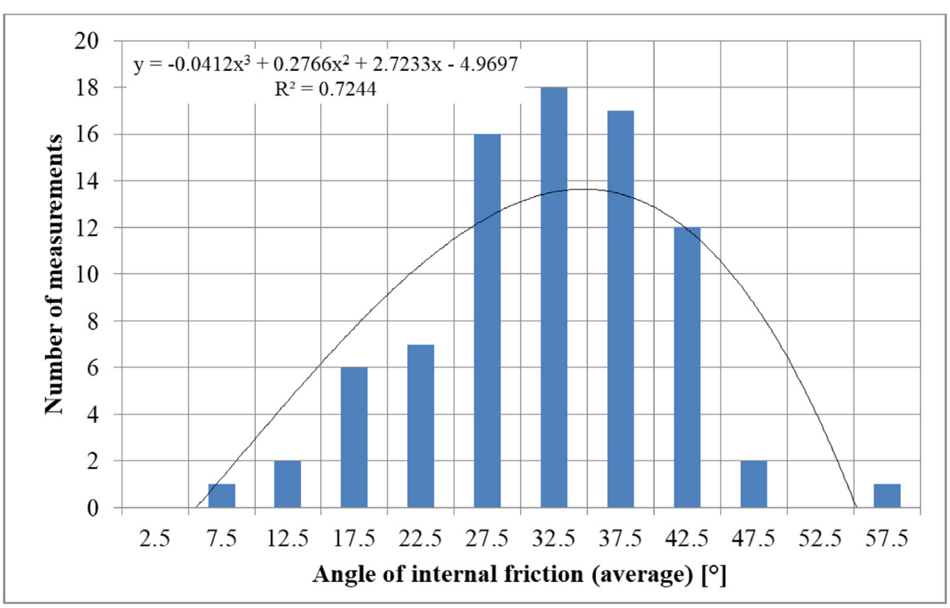

Fig. 9. Distribution of variation of the friction angle of municipal waste depending on the number of measurements [15,33,60].

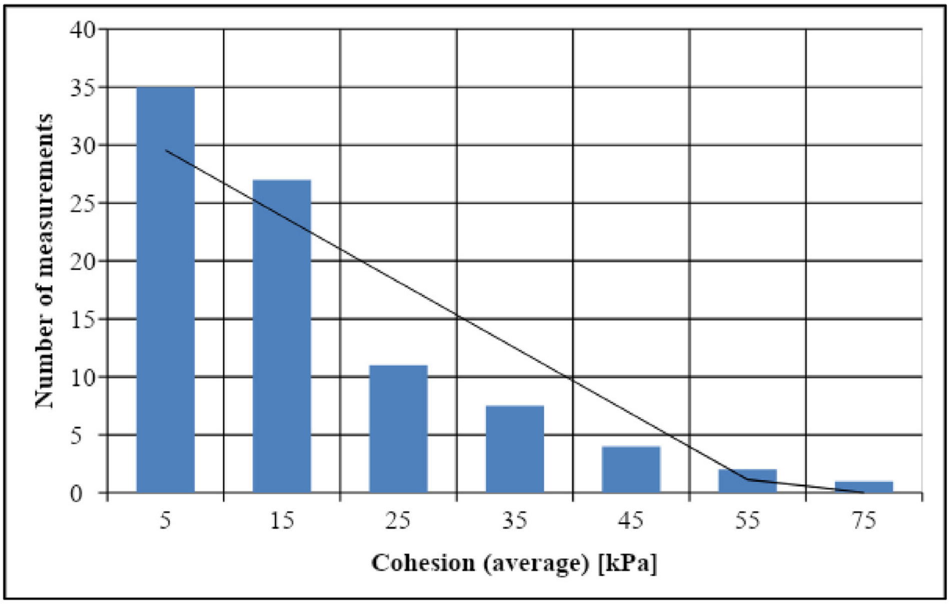

Fig. 10. Distribution of variation in municipal waste cohesion as a function of the number of measurements [15,33,60].

– Variation III – analysis of the stability of the municipal landfill for a constant value of the angle of internal friction equal to 45° and for a variable value of cohesion in the range from 0 to 50 kPa.

Table 2 summarises the mechanical parameters of municipal waste for these calculation variations.

Mechanical parameters of subsoil for numerical modelling was adopted from Table 1.

3.6. Slope stability acceptance criteria

The factor of safety (*FoS*) and probability of failure (*PoF*) are commonly used to estimate the risk of slope failure (Table 3).

Table 2. Mechanical parameters of municipal waste for numerical modelling.

Density [kg/m^3]	Young modulus [kPa]	Poisson ratio [-]	Angle of internal friction [°]	Cohesion [kPa]
Variation I				
900	3000	0.4	15	0
				25
				50
Variation II				
900	3000	0.4	30	0
				25
				50
Variation III				
900	3000	0.4	45	0
				25
				50

Table 3. Typical design acceptance criteria for open pit slopes [61].

Slope type	Case	Acceptability criterion	
		FoS	*PoF* (%)
Global	Final wall	>1.30	<12
		>1.45	<10
		>1.60	<8

During the stability analysis, it was assumed that the slopes should be characterised by long-term stability and the occurrence of landslide processes must be very unlikely (Table 4).

4. Results analysis and discussions

The factor of safety for every single calculation variation given in Table 2 was calculated. Because of the large number of outcomes, the results of selected calculation variation are presented. Figure 11 presents an example of *FoS*, calculated for variation II. For this calculation variation, all values of *FoS* are greater than 1. The possible failure is located at the west-south wall of the slope. It also

Table 4. Landslide hazard level classification due to FoS value [62].

Probability of landslides		Safety of slope
very unlikely	$FoS \geq 1.5$	safe
unlikely	$1.3 \leq FoS < 1.5$	
likely	$1.0 \leq FoS < 1.3$	unsafe
very likely	$FoS < 1.0$	

Based on the given criteria, it can be assumed that ensuring a sufficiently high level of safety for the landfill site slope requires a *FoS* value greater than 1.3.

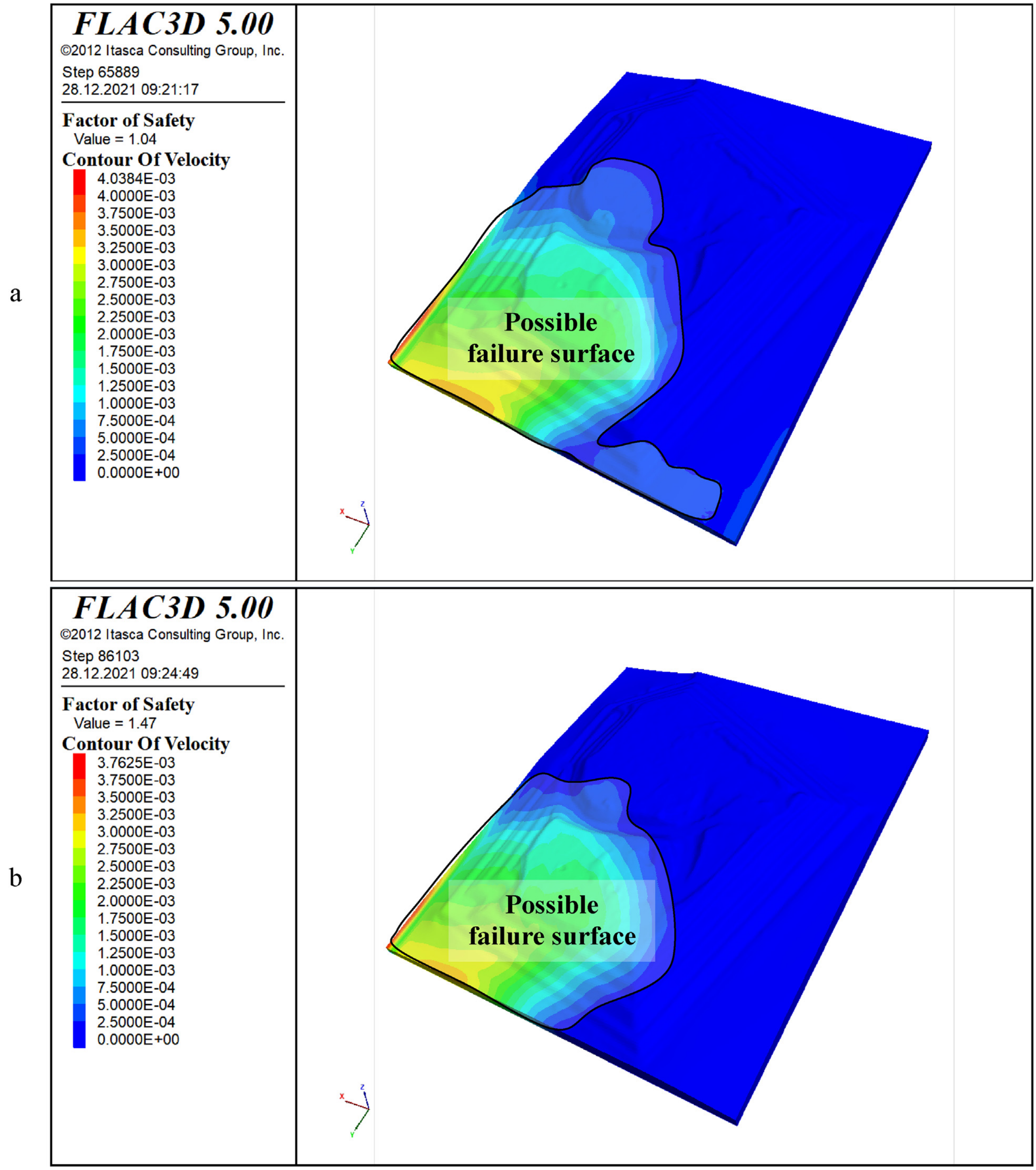

Fig. 11. Factor of safety plot for an internal friction angle of 30° with different value of cohesion: a) 0 kPa; b) 25 kPa; c) 50 kPa.

can be noted that the size of the possible failure decreased with the increase of cohesion value.

A summary of all calculated *FoS* values is shown in Table 5.

The results can be drawn as follows:

- In case of non-cohesive waste (cohesion is close to or equal to 0), the landfill slope is considered unstable (*FoS* less than 1) with a value of friction angle less than 30°. Failures were observed on the entire slope and local slope benches. With a value of friction angle from 30° to 45°, the slope is considered stable but not safe for long-term operation. Possible failure is observed at the west-south part of the slope (Fig. 9a). The landfill slope becomes stable and safe in long-term c

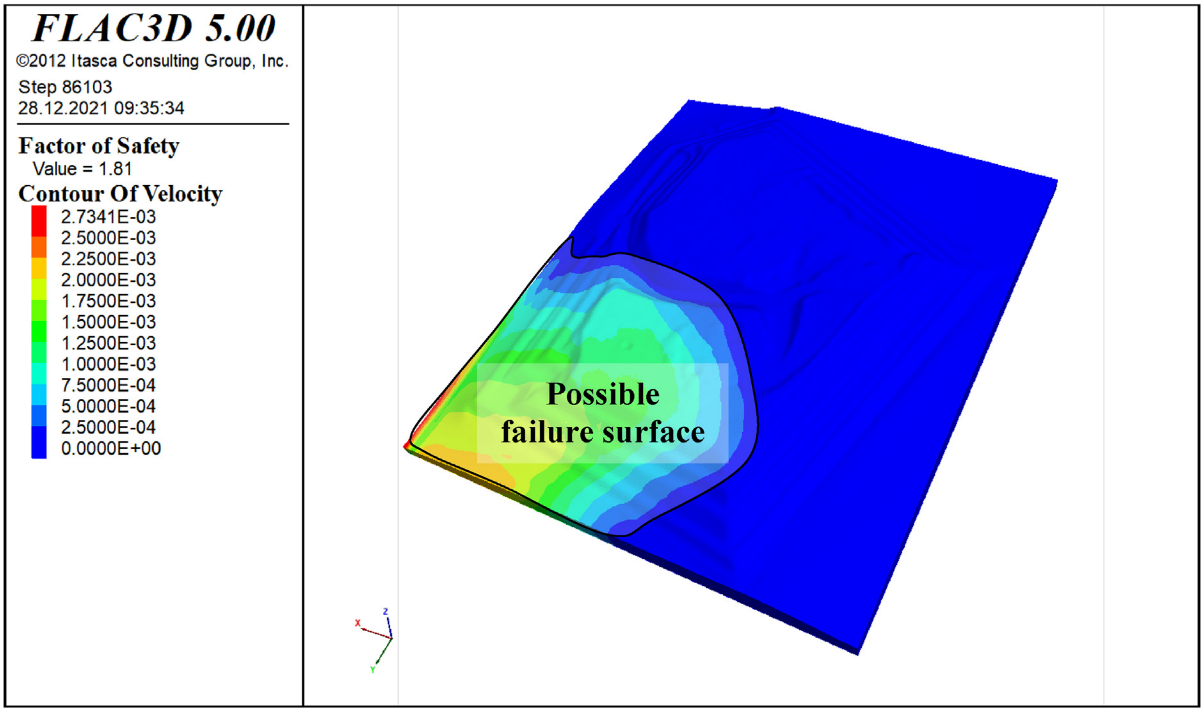

Fig. 11. (Continued).

Table 5. Calculated FoS values for all variations.

FoS		Cohesion, kPa		
		0	25	50
Angle of internal friction, °	15	0.42	1.02	1.38
	30	1.04 (Fig. 9a)	1.47 (Fig. 9b)	1.81 (Fig. 9c)
	44	1.43	1.88	2.24

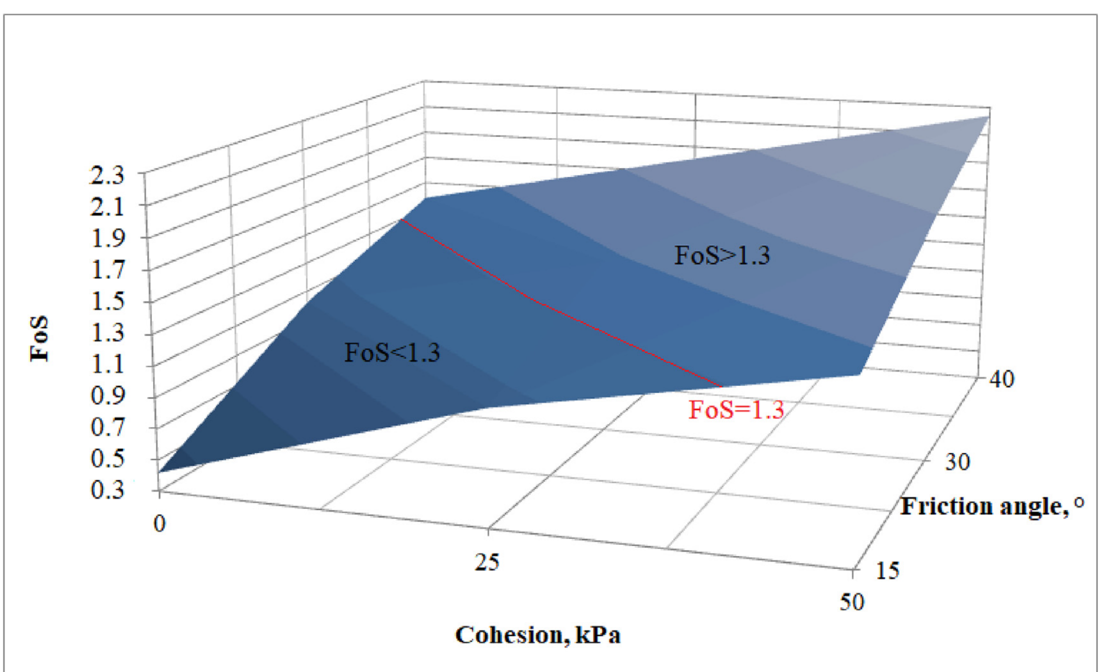

Fig. 12. FoS values versus the cohesion and angle of internal friction.

operation if the friction angle is higher than the value of 45°

- In case of a higher value of cohesion, up to 25 kPa, the landfill slope is considered stable with the value of *FoS* in a range of 1.02–1.88. If the friction angle is less than 30°, the slope is considered likely unsafe for long-term operation. Possible failure can be observed at the west-south part of the slope. Otherwise, the slope is considered safe (friction angle > 30°) (Fig. 9b).
- In case of a high value of cohesion such as 50 kPa, landfill slope is considered stable and safe for any value of friction angle (Fig. 9c).

Based on the results shown in Table 5, a design chart was formed, as shown in Figure 12. It can be noted that the landfill slope safety factor has increased along with an increase in both friction angle and cohesion. With such a design chart, the *FoS* value can be rapidly estimated after the shear strength values are given. Consequently, it would help managers improve planning and design for their landfills.

If the landfill slope safety factor $FoS \geq 1.3$, it meets the requirements. Then, a certain volume of the municipal waste can be safely placed on the current landfill slope. If the landfill slope safety factor $FoS < 1.3$, it does not meet the requirements. Therefore, it should be designed for slope stabilisation measures under the slope failure characteristics. Practically, the slope stabilisation measures for soil slopes can be adopted for landfill slopes from basic cheap measures such as: spreading and compacting, steel mesh, geogrids, geotextile or geosynthetics [e.g. 63–65] to advanced measures such as retaining walls, Larssen sheet piling or deep foundation installation.

5. Conclusion

Ensuring the stability of the municipal landfill slope is a key issue to maintain the continuous operation of these facilities. This paper proposes a methodology for the assessment of safe surface areas of a municipal landfill site for further waste disposal based on the results of numerical simulations. Analysis was conducted using the FLAC3D program, taking the variability of friction angle and cohesion into consideration. The results obtained allowed us to formulate the following conclusions:

– The numerical analysis using FLAC3D managed to predict waste material storage areas based on the municipal landfill slope stability analysis. Such an analysis can be repeated for the updated geometry of the landfill site during its deposition process. This study has highlighted the key advantages of numerical modelling as a useful tool for solving complex geotechnical issues.
– Results have shown that the stability of the slopes of a municipal waste landfill depends on the friction angle and cohesion of the municipal waste material. It has also been confirmed in other studies. Therefore, it is crucial to conduct detailed geotechnical tests of municipal waste in any individual case.
– Numerical analysis provides opportunities to determine areas of the municipal landfill site where there is potential for continued material disposal safely. Based on the given design chart, the stable or unstable area of the landfill will be rapidly determined based on the results of the geotechnical tests conducted with the values of friction angle and cohesion. It would assist managers and owners in making decisions.
– Due to the uncertainty regarding the properties of landfill waste, continuous monitoring systems (e.g., automated/semi-automated online) should be carried out at the landfill site in order to provide up-to-date movement of landfill slope. It would prevent possible landslides. Moreover, results from monitoring could be useful to verify and confirm the numerical results in the next stages.
– Except for traditional practices, such as spreading and compacting the waste on the working surface, it is also suggested to apply professional landslide prevention measures for typical soil slope such as steel mesh, geogrids, geotextile, geosynthetics or nailing with steel mesh, whether even retaining walls, Larssen sheet piling, deep foundation installation if necessary, in order to ensure safety in the long-term planning of the municipal waste landfills.

Ethical statement

The authors state that the research was conducted according to ethical standards.

Funding body

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Conflicts of interest

The authors declare no conflict of interest.

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