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Analysis of the Influence of Waste Shear Strength Parameters on Landfill Slope Stability

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Abstract – In this paper, the influence of waste shear strength parameters on landfill slope stability is studied. Namely, using the limit equilibrium method in GeoStudio 2018, stability analyses of a typical landfill slope are performed using semi-probabilistic and probabilistic approaches. The semi-probabilistic computations of slope stability are performed based on the available literature recommendations for the waste shear strength parameters. The results obtained for different recommendations are compared and discussed. In the probabilistic computations, the waste shear strength parameters are treated as random variables with Gaussian random distribution, where the parameters of the distribution are again selected based on the literature recommendations. Here, the influence of dispersion in the values of waste shear strength parameters is also examined. In addition, sensitivity analyses are also performed to gain insights into the relative importance of parameters. With the aforementioned analyses, an effort was made to investigate and derive conclusions about how the selection of waste shear strength parameters affects landfill slope stability.

***Keywords*:** landfill, slope stability, waste, shear strength parameters, semi-probabilistic analysis, probabilistic analysis, sensitivity analysis

1. Introduction

Modern sanitary landfill is a method of controlled waste disposal that involves waste treatment and various systems for soil, water, and air protection. The primary objective is to minimize environmental and public health risks associated with waste management. In the design of a landfill, slope stability is an important consideration. Namely, landfill typically consists of multiple slopes, including both natural and man-made slopes. Hence, slope stability has to be carefully analysed to prevent slope failures, which can result in environmental hazards and pose risks to human safety.

A landfill slope stability analysis involves defining the geometry and identifying all the components of the landfill that can influence the overall stability, selecting the input parameters for all the components and underlying soil, and also choosing the appropriate method of analysis.

The landfill slope stability is directly influenced by the properties of the disposed waste. The disposed waste consists of a wide range of waste components, each with different physical, mechanical, chemical, and biodegradable properties. As gases and leachate circulate within the landfill and waste components undergo biodegradation, the phase composition of the waste varies and tends to change over time [1]. Hence, the high heterogeneity of the waste is apparent and the waste properties change not only spatially but temporally as well.

The unit weight and the shear strength of the waste are crucial input factors in conducting an accurate and reliable landfill slope stability analysis. The shear strength of waste is commonly described using the Mohr-Coulomb model, with the cohesion (c) and angle of internal friction (φ) as the shear strength parameters. The shear strength parameters are influenced by various factors due to the inherent heterogeneity of waste. These factors include the composition of waste, such as the presence of organic and reinforcing materials, as well as the age of the waste and the degree of decomposition. Furthermore, the shear strength parameters can also be influenced by other factors related to waste disposal technology, such as the degree of compaction and the thickness of each waste layer, among others [2].

Shear strength parameters can be determined through various methods, including laboratory tests on large and/or small samples, in-situ tests conducted on landfills, and back-analysis performed on existing landfills. Among the laboratory tests frequently utilized for determining shear strength parameters of waste are the direct shear test and the triaxial test. In terms of in-situ testing, the direct shear test on larger sample sizes and the standard penetration test are commonly employed. Back-analyses involve analysing the observed behaviour of the slope or previous slope failures to estimate the waste strength parameters that would produce a reasonable fit between the observed and computed responses. A comprehensive overview of the results from studies conducted by various authors utilizing the aforementioned methods can be found in [3,4]. By analysing the available literature data, it is evident that there is a significant variation in the values of shear strength parameters. This wide range of values makes it challenging to draw any definitive conclusions. Due to this, when performing the landfill slope stability analysis, the selection of appropriate waste strength parameters is a crucial concern.

As mentioned previously, in a landfill slope stability analysis an appropriate method of analysis has to be selected. The method of analysis could involve the limit equilibrium methods, numerical methods, or a combination of both. Due to the heterogeneity of the waste, in addition to the semi-probabilistic approach that involves the application of characteristic values of material properties in combination with partial factors of safety as suggested in Eurocode 7 [5], the probabilistic approach can provide further insights into the landfill slope stability, critical parameters that contribute most to the uncertainty and the associated risk. Probabilistic analysis of landfill slope stability involves considering the uncertainties and variability in input parameters to assess the probability of slope failure. Instead of relying on characteristic values for input parameters, probabilistic analysis takes into account the inherent variability in waste properties, and other factors influencing slope stability. In this analysis, the input parameters are treated as random variables with known probability distributions, usually Gaussian random distribution. Monte Carlo simulation or other probabilistic methods are then used to generate multiple sets of input values by sampling from these distributions. Each set of input values is used to perform a slope stability analysis, resulting in a distribution of computed factors of safety or probability of failure. A probabilistic approach is particularly useful when dealing with complex and uncertain conditions, such as heterogeneous waste properties.

This paper focuses on investigating the relationship between the shear strength properties of disposed waste and landfill slope stability. The slope stability of a typical landfill is analysed using the GeoStudio 2018 [6], specifically the SLOPE/W module for limit equilibrium analysis and the SIGMA/W module for finite element analysis to compute the initial stress state. Given the heterogeneity of the waste, the stability analyses include semi-probabilistic analyses based on the waste shear strength parameters values recommended by various authors, probabilistic analyses, and sensitivity analyses. The main details on the geometry, the input parameters, and the analyses performed are given in Section 2. The computed results are presented and discussed in Section 3. The concluding remarks are summarized in Section 4.

2. Problem Statement

2.1. Geometry and Input Parameters

The landfill slope geometry analysed in this study is shown in Fig. 1. The selected side slope ratio is 1:3. The height of the waste within the landfill is varied from 10 m to 40 m. An embankment is constructed at the foot of the slope, which serves to enhance stability and facilitate the disposal of initial waste layers. The height of the embankment at the foot of the slope is 1:4 in relation to the height of the slope. The sides of the embankment have a slope ratio of 1:1.5. The top width of the embankment is 6 m.

The objective of the subsequent analyses is to examine how the shear strength parameters of the waste affect the landfill slope stability, specifically when the sliding surfaces pass through the waste. Due to this, the analyses do not consider the bottom liner system of the landfill. Additionally, the underlying soil is modeled as a solid rock.

In relation to the unit weight of the waste (γ), it is commonly recommended by most authors to be within the range of 8,8 to 10,0 kN/m^3 for well-compacted waste [2,3]. In modern sanitary landfill practices, waste layers are effectively compacted using heavier machinery and multiple passes, leading to a narrower range of waste unit weight values compared to older practices. Therefore, a consistent value of $\gamma=10$ kN/m^3 is selected in all analyses. The selection of waste strength parameters will be further discussed in the subsequent section.

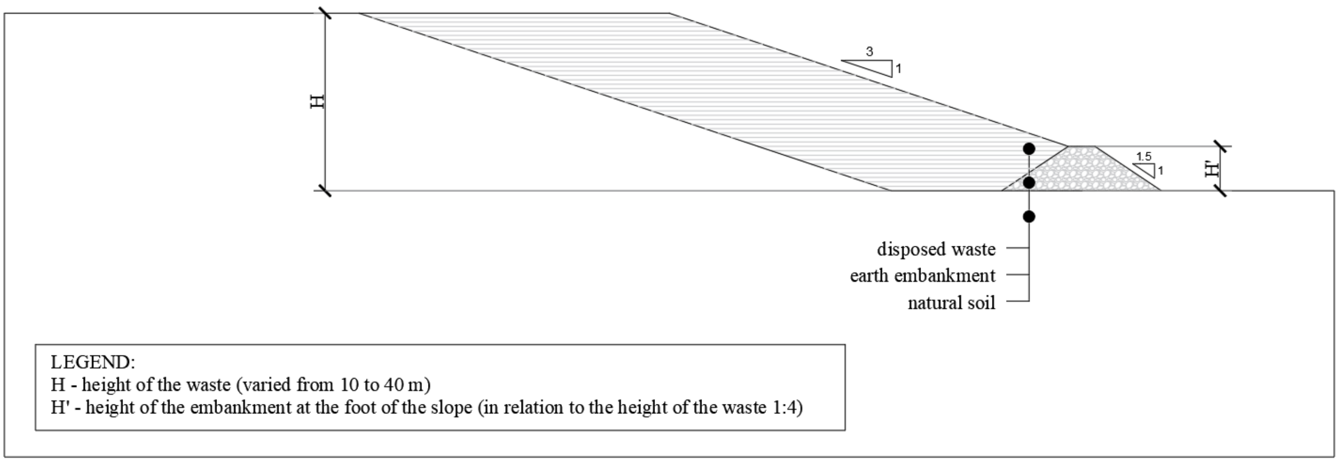

Fig. 1: Geometry of analysed landfill slope.

2.2. Methods of Analysis

The slope stability is analysed using GeoStudio 2018. The factor of safety of slope against the failure is computed in the module SLOPE/W using the limit equilibrium method, specifically the Morgenstern-Price method. The initial stress state is computed using the finite element method in the module SIGMA/W. Three types of analyses are performed: semi-probabilistic, probabilistic, and sensitivity. The details of these analyses are presented next.

2.2.1. Semi-Probabilistic Analyses

The semi-probabilistic analysis of slope stability relies on the characteristic values of loads and materials in combination with partial factors of safety, as suggested in Eurocode 7 [5]. The characteristic values represent expected values with a certain level of confidence. The partial factors of safety are introduced to account for the uncertainties in the design process. In the design process, the characteristic values are combined with partial factors of safety to obtain design values.

The end result of semi-probabilistic analysis of slope stability is a factor of safety (FOS) of the slope against failure. The FOS is simply a ratio of the resisting forces to the driving forces acting on the slope. According to Eurocode 7, the slope is considered to be stable if the computed FOS is greater than 1,25 for drained conditions or 1,4 for undrained conditions.

The waste strength parameters used in the semi-probabilistic analyses performed in this paper are adopted from the literature. Namely, in the absence of local data on waste shear strength parameters, several authors, including Jones and Dixon [7], Kavazanjian [8], and Van Impe [9], have provided recommended values to be utilized in such cases. Jones and Dixon recommend using $c=5$ kPa and $\varphi=25°$ as the strength parameter values. Kavazanjian suggests a combined approach with $c=24$ kPa and $\varphi=0°$ for normal stresses up to 30 kPa, and $c=0$ kPa and $\varphi=33°$ for higher stresses. Van Impe also recommends a combined approach, suggesting the use of $c=20$ kPa and $\varphi=0°$ for normal stresses up to 20 kPa, $c=0$ kPa and $\varphi=38°$ for normal stresses ranging from 20 kPa up to 60 kPa, and $c=20$ kPa and $\varphi=30°$ for higher stresses.

In his comprehensive study, Schneider [10] conducted an extensive analysis of laboratory results and back-analyses data available in the literature. As a result, he provided both mean and characteristic values of waste shear strength parameters. The characteristic values of waste strength parameters suggested by Schneider, derived from available laboratory and back-analyses data, are also used in the semi-probabilistic analyses performed in this paper. Based on available laboratory results, the characteristic values of waste shear strength parameters are determined to be $c=8{,}91$ kPa and $\varphi=25{,}58°$. Additionally, based on back-analyses data, the characteristic values of waste shear strength parameters are determined to be $c=12{,}65$ kPa and $\varphi=15{,}11°$. It can be noted, that the values of φ derived on the basis of back-analyses are significantly lower than the values derived from available laboratory data, whereas for the values of the c vice-versa applies.

2.2.2. Probabilistic Analyses

In the probabilistic slope stability analysis, the waste parameters are treated as random variables with known distributions, usually, Gaussian random distribution, which is defined with parameter mean value and standard deviation. The first step in a probabilistic slope stability analysis utilized in this study is the definition of a deterministic model, in which all the input data necessary to obtain a desired outcome are defined. Next, the probability distribution for all the parameters that are to be treated as random variables are defined. Then, the Monto Carlo simulation or other probabilistic method is used to generate multiple sets of these parameter values by sampling from these distributions. For each generated set FOS is computed using the limit equilibrium method, resulting in a distribution of computed FOS. The end result of the probabilistic analysis is a probability of slope failure (p_f) and reliability index (β), which are computed as [11]:

$$p_f = \frac{\text{number of failures}}{\text{number of simulations}} \cdot 100\% \tag{1}$$

$$\beta = \frac{\text{FOS}_m - 1}{\text{FOS}_{\sigma^2}} \tag{2}$$

where FOS_m is a mean value and FOS_{σ^2} is a standard deviation of computed FOS. For β=3, the slope can be considered stable.

In this paper, probabilistic analyses are performed for the mean values and standard deviations of waste strength shear parameters provided by Schneider [10], which are shown in Table 1.

Table 1: The waste shear strength parameters according to Schneider [10]

	Laboratory data		Back-analyses data	
	c (kPa)	φ (°)	c (kPa)	φ (°)
Mean value	18,18	29,74	24,23	20,84
Standard deviation	6,70	11,00	16,30	14,00

2.2.3. Sensitivity Analyses

A sensitivity analysis is performed to evaluate the influence of different parameters on the stability of the slope. This helps in understanding the relative importance of each parameter and identifying critical factors that significantly affect slope stability, for which further investigation or control measures during slope design and construction can be undertaken. In sensitivity analysis, the first step is to determine the parameters that affect slope stability. In this case, these parameters are waste shear strength parameters. Next, the range over which these parameters will be varied is specified. Then, one input parameter at a time is varied while others are kept constant and the change in computed FOS is analysed.

The values of the waste shear strength parameters, according to the recommendations of Jones and Dixon, Kavazanjian, Van Impe, and Schneider are in the interval c = 5-25 kPa and φ = 15-35°. Hence, sensitivity analyses in this paper are carried out for these specified intervals.

3. Results of Analyses and Discussion

3.1. Semi-Probabilistic Analyses

The computed FOS for different slope heights and recommended values of waste strength parameters are shown in Fig. 2. For all recommended values of waste strength parameters used in this paper, the computed FOS is greater than 1,25. Hence, the slope can be considered stable.

By comparing the computed values of FOS, it can be concluded that the FOS decreases with increasing slope height, regardless of the selected recommended values of the waste shear strength parameters. Furthermore, the highest values of the FOS correspond to the waste strength parameters recommended by Van Impe, while the lowest values are obtained when using the parameters recommended by Schneider, which he derived on the basis of back-analyses data. Values of waste strength parameters obtained on the basis of the laboratory results according to Schneider give approximately equal values of FOS to those obtained for parameters recommended by Kavazanjian.

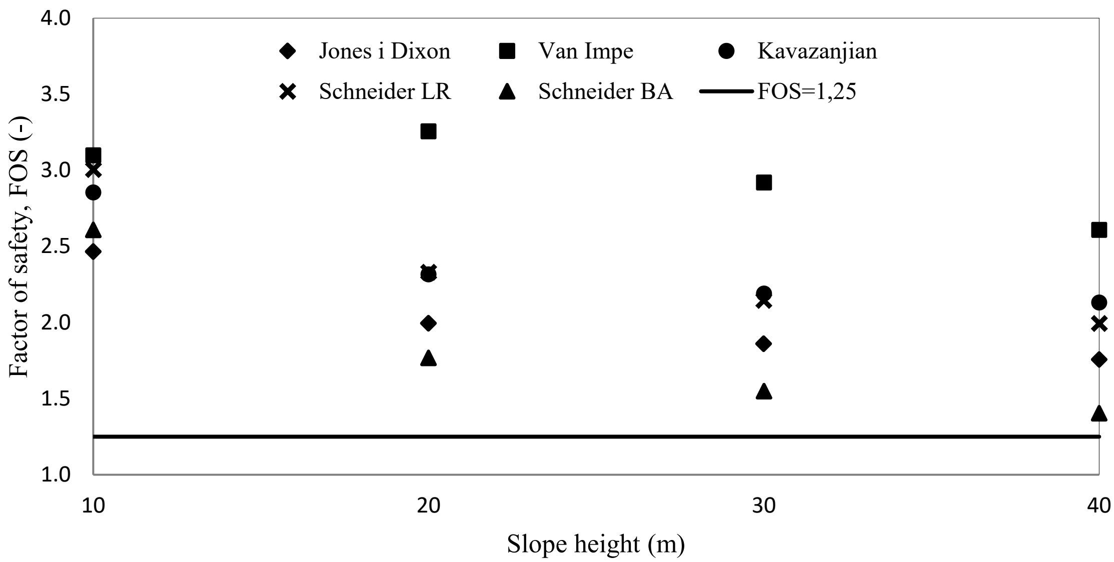

Fig. 2: Results of semi-probabilistic analyses.

For the slope height of 40 m, the highest computed value of FOS is 2,609, which is 86.42% higher than the lowest computed value, which is 1,404, indicating a significant range of computed values of the FOS depending on the selected recommendation. Hence, it is important to note that the use of such recommended values can provide a starting point but should be done with caution, and their applicability to a specific landfill site should be carefully considered. Site-specific conditions and waste properties can vary significantly, and if possible, local data should be collected and utilized for a more accurate assessment.

3.2. Probabilistic Analyses

The probabilistic analyses are first performed for variable slope height by considering both the c and φ as random variables that follow Gaussian random distribution with mean values and standard deviations provided by Schneider. The computed values of the reliability index β are shown in Fig. 3.

By comparing the computed results, it can be concluded that β decreases with increasing slope height. As slope height increases from 10 m to 40 m, the value of β decreases by 34,8% for laboratory results, and by 57,7% for back-analyses data. If it is adopted that β must be at least 3 for the slope to be considered stable, it follows that in both cases for all heights of deposited waste, the landfill cannot be considered stable because $\beta<3$. Moreover, the input parameters that define Gaussian random distribution obtained on the basis of back-analyses data give lower values of β than the parameters obtained on the basis of laboratory results.

Next, the influence of the standard deviation, which indicates the dispersion in the values of the waste strength parameters is investigated. The analyses were performed for the slope height equal to 40 m. The analyses are performed by first assuming that only one shear strength parameter is a random variable with varying standard deviation, whereas the other parameter is deterministic with a value equal to its mean value. Then, the analyses are again performed by now assuming that the other shear strength parameter is also a random variable with mean value and constant standard deviation provided by Schneider.

The computed results are shown in Figs 4-5. It can be concluded that in all cases an increase in the value of standard deviation, which means an increase in the dispersion of the waste strength parameters, results in a decrease in the value of β.

Furthermore, by analysing the results shown in Fig. 5a)-5b), it can be concluded that the values of β, for the case when both waste strength parameters are viewed as random variables, do not deviate significantly from the values for the case when only φ is viewed as a random variable. In other words, the dispersion of the *c* has a smaller impact on the analysis results.

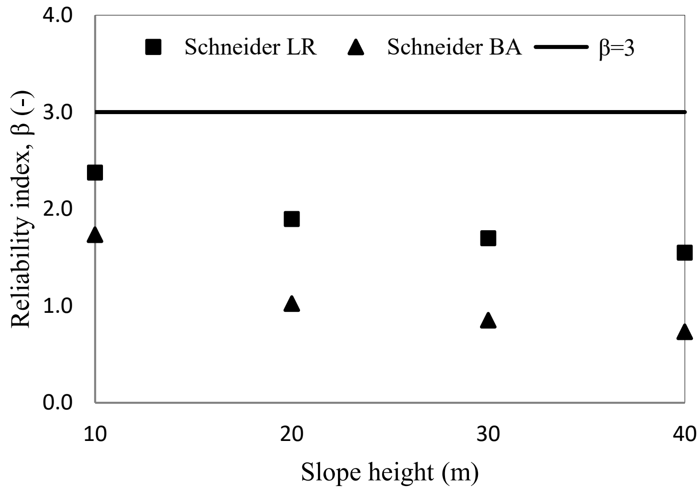

Fig. 3: Results of probabilistic analyses for variable slope height

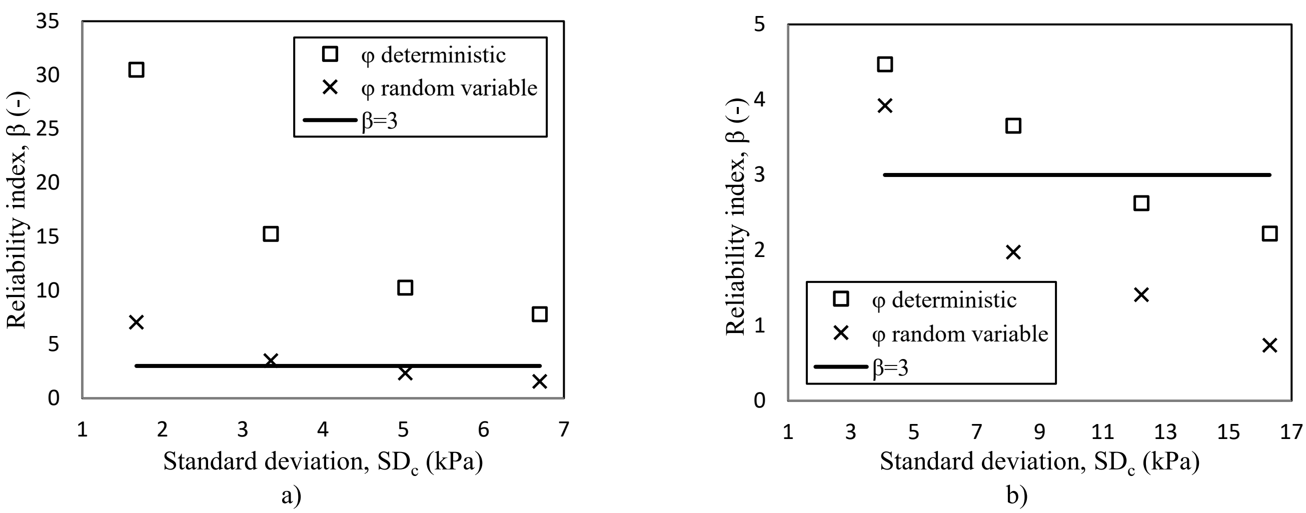

Fig. 4: Results of probabilistic analyses for variable standard deviation for *c*
a) laboratory results b) back-analyses data

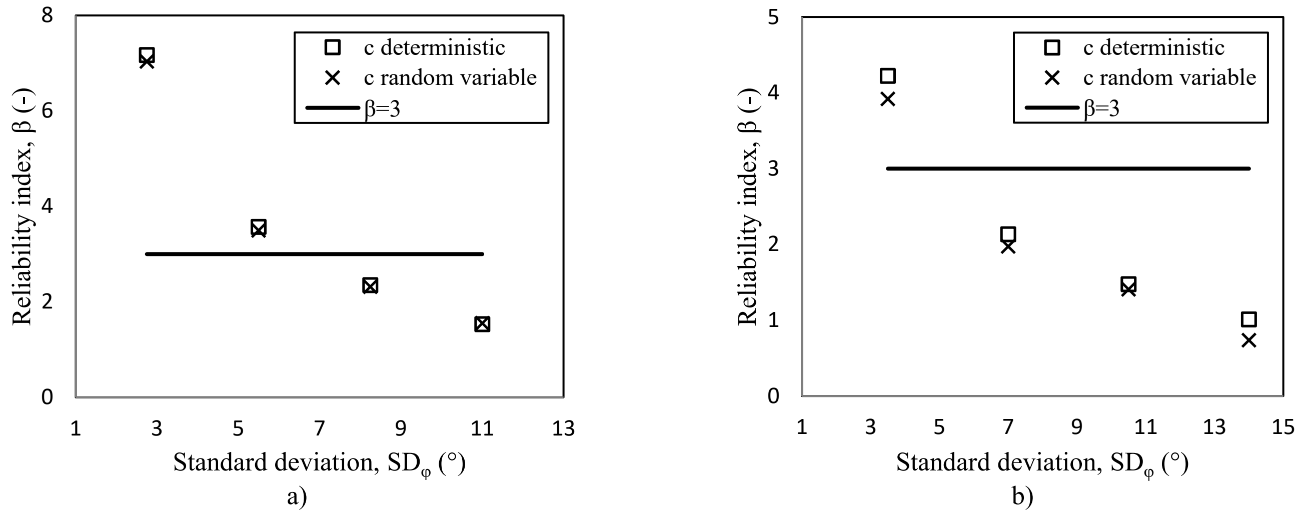

Fig. 5: Results of probabilistic analyses for variable standard deviation for φ
a) laboratory results b) back-analyses data

3.3. Sensitivity Analyses

The sensitivity analyses are also performed for variable slope height (*H*). The computed results for the cases when *c* and φ are varied in a predetermined interval are shown in Figs. 6a) and b), respectively.

For both cases, with an increase in the value of the parameter, the FOS increases linearly. However, the increase trend changes depending on the slope height and waste shear strength parameter that is varied. Namely, when *c* is varied, for $H=40$ m, the FOS increases by 34,95%, while for $H=10$ m the FOS increases by 96,58% (Fig. 6a). Hence, the influence of *c* is greater for smaller slope heights. However, when φ is varied, the influence is greater on the stability for higher slope heights. That is, for $H=40$ m the FOS increases by 107,5%, while for $H=10$ m FOS increases by 60,58% (Fig. 6b).

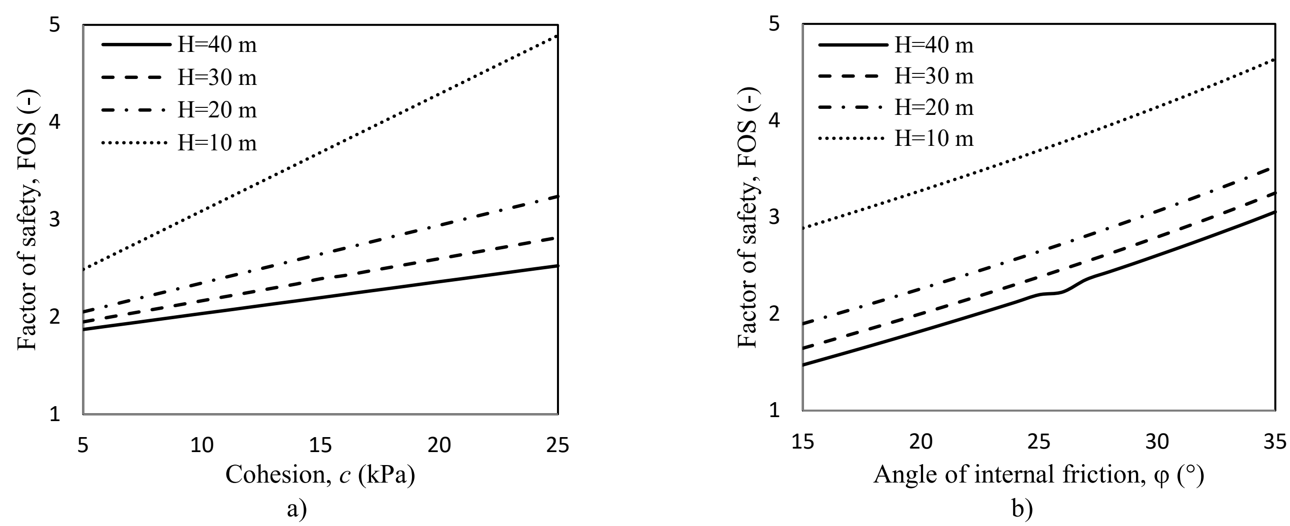

Fig. 6: Results of sensitivity analyses for variable a) *c* b) φ

4. Conclusions

In this paper, the variation of waste shear strength parameters on slope stability is investigated by performing semi-probabilistic, probabilistic, and sensitivity analyses. In all analyses, the basis for the selection of the waste shear strength parameters was literature recommendations. The results of semi-probabilistic analyses suggest a wide range of possible values of factor of safety of slope against failure depending on the selected literature recommendation. Therefore, while literature recommendations serve as a starting point for landfill design, they should be complemented with additional measures and considerations to ensure a comprehensive and robust design.

By analysing the results obtained for recommendations provided by Schneider, it can be concluded that in both semi-probabilistic and probabilistic analyses, the values of waste shear strength parameters derived on the basis of the back-analyses date result in lower slope safety compared to the values of waste shear strength parameters derived on the basis of the laboratory results. The results of probabilistic analyses indicate that the dispersion of values of c affects the slope stability to a lesser extent than the dispersion in the value of φ. And finally, the results of sensitivity analyses suggest that the change in the value of c has a greater impact for smaller slope heights, while the change in the φ value has a greater impact for greater slope heights.

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