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Geotechnical characterization of industrial waste and its stability in a landfill site

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ABSTRACT

Even though recycling strategies are becoming more important in recent years, a huge number of industrial by-products are disposed of at landfills. Due to the size, possible dangerous composition, and heterogeneity, most of the wastes are located in landfills without a basic geotechnical characterization. This lack of information may have an important influence on the results of the stability calculations. This paper presents the results of the geotechnical characterization of some industrial wastes, coming from end of live vehicles, once disposed of at one landfill. The shear strength properties were determined based on direct shear test results carried out in a large shear box owned by CEDEX, which has a shear plane of 1 x 1 m. The tests were also performed in a 30x30 cm shear box. The present work also describes the bases of design for the global stability analysis of a landfill, by the definition of the relevant design situations, the sliding surfaces to be analysed, the piezometric levels to take into account and the material properties necessary to develop the calculations. Not only the theoretical framework is described but it also explained by an example of a global stability analysis of a landfill for industrial wastes. The stability calculations were performed for various hydrological scenarios to simulate the performance of the leachate drainage system.

Keywords: Industrial waste, landfill, stability.

1 INTRODUCTION

In 2020, 4.8 tonnes of waste were generated per European Union (EU) inhabitants (Eurostat 2021), and 38.5% of this waste was placed in landfills. Due to the problems associated with this huge amount of waste, the EU is fostering policies toward a circular economy model. In this model, materials are reused and recycled back into the cycle as much as possible, to keep the waste at a minimum amount.

The automotive industry is one of the most resource-consuming industrial production sectors, and so is waste generation. End-of-life vehicles (ELVs) are collected, dismantled, and partially recovered. According to Eurostat (2021), the total number of ELVs, in the EU, was 6.9 million in 2019. Since 2015, forced by ELV Directive (2000/53/CE), EU Member States are required to meet rates for reuse and recycling, as it is described in this Directive: *"…no later than 1 January 2015, for all end-of-life vehicles, the reuse and recovery shall be increased to a minimum of 95 % by an average weight per vehicle and year. Within the same time limit, the re-use and recycling shall be increased to a minimum of 85 % by an average weight per vehicle and year".* Despite the high percentage of ELV recovery, there is still an important volume of material that is unfortunately disposed of in landfills.

The Landfill Directive (1993/31/EC) sets out strict operational requirements for landfill sites to protect both human health and environment. It also aims to reduce reliance on landfill as a disposal. Landfills are classified into three classes: landfill for hazardous wastes, landfill for non-hazardous wastes and, landfill for inert wastes. Annex I includes some general requirements related to ground and groundwater protection and global stability. The first requirement indicates that *"Protection of soil, groundwater and surface water is to be achieved by the combination of a geological barrier and a bottom liner during the operational phase".* The landfill base and sides shall reach specific permeability values (depending on the type of landfill), and where the geological barrier does not meet these conditions, the protection shall be achieved by the placement of a bottom liner, mostly formed by geosynthetic layers (named as waterproofing package, in this paper). The requirements relative to the landfill global stability only

indicate that: *"The emplacement of waste on the site shall take place in such a way to ensure stability of the mass of waste and associated structures, particularly in respect of avoidance of slippages".* In the case of the use of a waterproofing package, the text only requires that settlements of the site ground do not cause damage to the package.
As explained above, despite the efforts of the EU to minimize the amount of waste to be placed at landfills, they are still necessary. The landfills must be stable and guarantee that wastes are isolated from the ground and groundwater, which is frequently obtained by using geosynthetic materials in the waterproofing package. It must be highlighted that the type and characteristics the waterproofing package used has a relevant impact on the global landfill stability.

2 INDUSTRIAL WASTE DESCRIPTION AND GEOTECHNICAL CHARACTERIZATION

When vehicles have ended their useful lives, they must be sent to an authorized treatment facility where are dismantled and partially recovered (mainly their metal fractions such as ferrous materials, aluminium, copper, zinc and stainless steel). The remaining material is shredded and known as "Automotive Shredder Residue" (ASR), mainly consisting of non-metallic materials. ASR material represents around 25% of the vehicle weight, and it is also called "fluff". Morselli et al. (2010) studied the composition of fluff samples, indicating the following constituents: 45% of fines, not able to determine the composition but with a large number of metals, 18% foam rubber, 15% rigid plastic, 9% textile, 7% rubber, 4% soft plastic, 1% metals and 1% cellulosic.

Two different samples of ASR or fluff material placed in a landfill were in-situ collected to study their geotechnical characteristics: a) Fluff with a maximum size of 10-15 cm (named as Fluff 10-15 cm), and b) Fluff after screening and a maximum size of 2-3 cm (named as Fluff 2-3 cm). Both samples were mainly composed of plastics, foam rubber and metals. Figure 1 shows a photograph of these materials once in the laboratory.

Figure 1. *Fluff 10-15 cm (left). Fluff 2-3 cm (right)*

The geotechnical characterization was focused on the strength properties for performing subsequence stability analysis. The Fluff 10-15 cm sample was tested in the large direct shear box, belonging to CEDEX, which has a shearing plane of 1 x 1 m (Figure 2). With those dimensions, the maximum particle size to be used in the tests is 15 cm, so, in this case, that limitation is fulfilled. The maximum vertical load and the maximum horizontal displacement that can be imposed on the material are 1000 kN and 25 cm, respectively. The horizontal load, with a maximum of 1000 kN, can be imposed at a constant speed, ranging from 0.5 to 45 mm/min. This equipment was extensively used to study rockfills for use in ports and dams (Estaire and Olalla, 2006). In recent years, investigations with this device have been

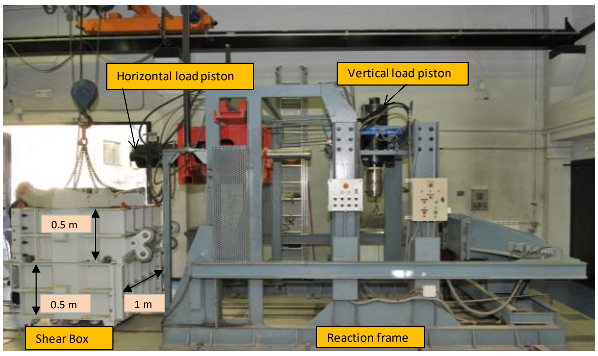


Figure 2. *Photograph of the large direct shear test device used in the tests*

focused on railway ballast (Estaire and Santana, 2018). The Fluff 2-3 cm sample was tested in a standard 30x30 cm shear box.

The vertical stresses applied in both tests were 50, 100, 200 and 400 kPa. Moreover, the weight density obtained after the consolidation process was lower than 10 kN/m^3, for the Fluff 10-15 cm sample, and between 13 and 16 kN/m^3, for the Fluff 2-3 cm sample. According to the topographic control of the landfill, the weight density of the waste once placed is between 12 and 13 kN/m^3. Figure 3 collects all the values for the pairs of normal stress applied and shear strength obtained for the two samples and the Mohr-Coulomb lines that best fit the results.

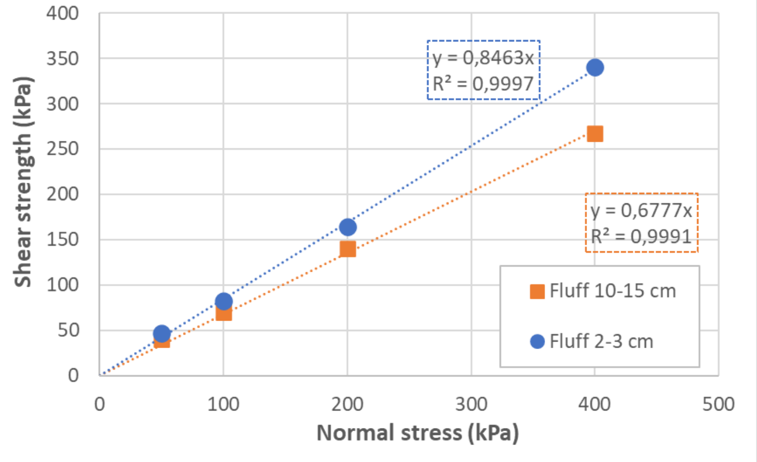


Figure 3. *Direct shear test results for fluff samples*

The results were interpreted by the Mohr-Coulomb failure criterion, just for frictional behaviour, that is neglecting cohesion, obtaining the following friction angles:

- Fluff 10-15 cm sample: 34º
- Fluff 2-3 cm sample: 40º

It is important to highlight that calculations should be made with representative values that should be understood, in this case, as a conservative estimate of the average value. Due to the fact that only two laboratory tests are available, it was considered that the mean value for the friction angle obtained should be decreased by a value close to the value of the coefficient of variation. Duncan (2000) estimates a coefficient of variation for friction angle between 2-13%, meanwhile, the future Eurocode EC-7 set the threshold between 5-15%. For this study, and taking into account the EC7 reference, a coefficient variation of 10% was set, resulting a representative value for the waste shear resistance of 30º.

3 BASES OF DESIGN FOR THE ANALYSIS OF GLOBAL STABILITY OF LANDFILLS

3.1 Introduction

The global stability analysis is one of the requirements for all landfill projects. As it was mentioned above, the Landfill Directive indicates that the landfill and the wastes placed in it must be stable, but it does not mention more requirements or the procedure to study this aspect. In Spain, a draft of a technical document for the stability of landfills exists with some general guidelines (Subdirección General de Calidad Ambiental, 2003).

This chapter aims to define the theoretical framework for the stability analysis and the data necessary for the calculations. The bases of calculations are:

- Design situations to analyse,
- Sliding surfaces to consider,
- Values of the safety factor required for the various design situations.

Moreover, the data necessary to carry out the calculations are:
- the geometry of the landfill profile to be calculated,
- the piezometric levels to be considered, and,
- the strength properties of the materials involved in the calculations.

3.2 Design situations

Usually, four design situations must be considered, which represent four different situations to which landfills can be exposed during their design life: normal, accidental, extraordinary and seismic.

3.2.1 Normal situation

It corresponds with usual, well-functioning operations in the landfill. This situation implies that there has not been any significant movement of the wastes and that the piezometric level is the one corresponds with the normal functioning of the leachate collection system.

It is important to note that this piezometric level only affects the wastes inside the landfill and, therefore, does not affect the waterproofing package. This implies in the stability calculations that, below the waterproofing package, there would only be the groundwater pressures derived from the piezometric level that could exist in the natural ground. In the most extreme case, the piezometric level of the natural ground could be on its surface but would be relieved by the basal drainage system of the landfill.

3.2.2 Accidental situation

It is a situation produced by the rupture or malfunctioning of some element of the landfill, such as failure of the drainage system. This situation implies that the leachate collection system gets clogged or otherwise fails to work, and, consequently, there is an unexpected raise in the leachate level inside the waste. Usually, these situations can be considered temporary.

As in the normal design situation, it is important to note that this piezometric level only affects the wastes inside the landfill and, therefore, does not produce over groundwater pressure in the waterproofing package.

3.2.3 Extraordinary situation

This situation, with a very low probability of occurrence, can appear as a consequence of an extended accidental situation, corresponding to a failure of the waterproofing package, if no measures are taken to repair it. In this stage, due to the weight of the fill, great movements of the wastes can be produced along the waterproofing package provoking a situation which can be identified with a global failure of the landfill.

In this extraordinary design situation, the piezometric level existing in the industrial waste also produces groundwater pressure inside the waterproofing package, since it was assumed that this package was ruptured so both piezometric levels are connected.

3.2.4 Seismic situation

This design situation combines a normal situation with the occurrence of a seismic event. This situation can be analysed by performing pseudo-static calculations with inertial horizontal and vertical forces to model the seismic effects.

3.3 Sliding surfaces to be analysed

The design calculations described above do not mention the geometry of the sliding surfaces to be considered in each case. According to the recommendations of the Spanish draft document for landfill stability, the following geometries of the sliding surface should be studied:
- Sliding surface through the landfill and natural foundation ground.
- Sliding surface through the waste fill.
- Sliding surface along the waterproofing package assuming the lowest strength of its interfaces.

This work has not included the stability analysis of the slopes of the external profile of the wastes that usually are covered by an upper sealing since it was considered that the appearance of instabilities in these areas would involve a small volume of waste. This reason does not exempt the need for its calculation in real landfill projects.

3.4 Minimum values required for the global stability safety factor

The landfill stability is verified if the safety factor obtained with calculations is greater than a minimum value set by the National Authorities. To set the most appropriate minimum safety factor to be reached, for this work, two Spanish documents were reviewed: the draft of the technical document mentioned above and the Technical Guides on Dam Safety (Guía Técnica de Seguridad de Presas, 2003). This aspect was also analysed by Estaire and Santayana (2012).

The draft of the technical document for landfill stability includes minimum safety values as a function of the type of landfill and the risk involved in a landfill failure. These values are included in Table 1.

Table 1. *Minimum global stability safety factors for landfills (from Draft Technical Document for landfill stability)*

	Classes of landfill		
Risk	**For Inert wastes**	**For Non-hazardous wastes**	**For Hazardous waste**
Low	1.30	1.40	1.50
Medium	1.40	1.50	1.60
High	1.50	1.60	1.80

This document specifies that *"low-risk situations are those in which a potential instability would exclusively cause material damage without significant consequences for the environment or for the safety of people. Medium risk is meant the situation of a landfill whose instability would cause significant damage to the environment but not for the safety of people. High-risk situations are those in which damage to people or severe environmental impacts or irreversible*".

On the other hand, the minimum safety values included in the Technical Guides on Dam Safety are set as a function of the dam category and the type of design situation. These values are included in Table 2.

Table 2. *Minimum safety factors from Technical Guides on Dam Safety*

Design situation		Dam Category	
	Category A	**Category B**	**Category C**
Normal	1.40	1.40	1.30
Accidental	1.30	1.20	1.10
Extreme	>1.00	>1.00	>1.00

The text indicates that Category A dams are those dams whose failure can cause very significant material and environmental damage. A failure of a Category B dam could cause major damage or affect a small number of people, and a failure of a Category C dam would cause only minor material damage and only exceptional loss of human life.

Considering the previous documents, in this work, the minimum global stability safety factor to reach in each design situation is shown in Table 3.

Table 3. *Minimum global stability safety factors adopted in this work*

Design situation	**Description**	**Minimum safety factor**
Normal	Normal operation of landfill	1.50
Accidental	Drainage system clogging	1.40
Extraordinary	Breakage of waterproofing package and its saturation	1.20
Seismic	Earthquake with normal operation landfill	1.20

4 EXAMPLE OF AN STABILITY ANALYSIS OF A LANDFILL FOR INDUSTRIAL WASTE

4.1 Introduction

This chapter includes an example of the stability analysis of a landfill for industrial wastes, considering the bases of design developed in the previous section. Firstly, the landfill main characteristics are described, such as the topographic profile, the bottom waterproofing package, the type of materials placed, and the piezometric levels considered. Secondly, the results of the calculations performed for the different design situations are described. Finally, due to its relevance in the stability conditions, the relation between the global stability safety factor and the piezometric level location inside the wastes is included.

4.2 Description of the landfill for industrial waste

In this study, the stability calculations were performed for a non-real landfill but modelled based on the authors´ experience and due to the significant number of the landfill located at natural gluches.
Topographic profile: landfill is located at a natural gulch. The gulch base has two slopes: the lower one that is almost horizontal, and the top one with a general slope of 30º. The natural ground is worked to obtain 10 m high slopes with 2H:1V inclination. The external profile has a general slope of 18º (3H:1V) with individual slopes of 10 m high, 2H:1V inclination and 7 m width. The stability analyses were performed for the landfill at its maximum capacity to be reached at the end of its design life (see Figure 4).

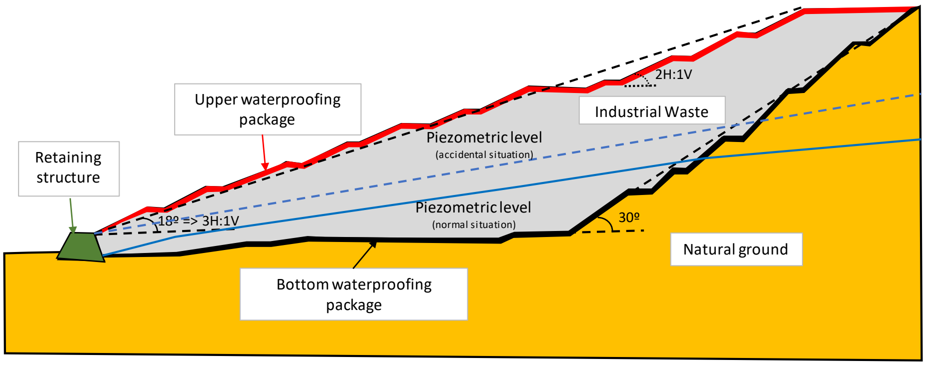


Figure 4. *Scheme of the profile of the landfill for industrial wastes used in the stability analysis*

Industrial wastes: landfill was filled with non-hazardous industrial wastes resulting from ASRs whose main geotechnical properties are:

- Friction angle: 30º (without cohesion)
- Apparent weight density: 12,5 kN/m^3

Bottom waterproofing package: the isolation from groundwater and surface water was performed by a waterproofing package, formed by the following capping system (from bottom to top) and shown in Figure 5.

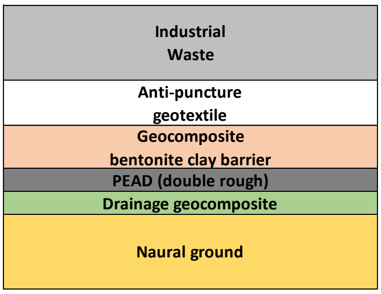


Figure 5. *Scheme of the bottom waterproofing package*

According to test results performed, the critical interface, in terms of shear strength or friction resistance, was the one between the geocomposite bentonite clay barrier and the anti-puncture geotextile. In this study, the whole waterproofing package was modelled as one layer with the strength properties of the critical interface. In this case, the geotechnical properties for this layer were:

- Friction angle: 26º for normal design situation, and 19º for accidental and extraordinary design situations.
- Apparent weight density: 12 kN/m^3

Over this capping layer system, industrial wastes were placed. For this study, the landfill was modelled without an upper waterproofing package, since its resistance is negligible for the landfill global stability.

Piezometric level: the stability analysis was performed assuming that, inside the landfill, exits a piezometric level due to the presence of leachates. This level is slightly different for the normal and accidental design situations, as shown in Figure 4.

Retaining structure: the landfill is closed by a reinforced fill structure at the low part of the gulch. The geotechnical properties assigned were:

- Friction angle: 50º
- Cohesion: 200 kPa
- Weight density: 19 kN/m^3

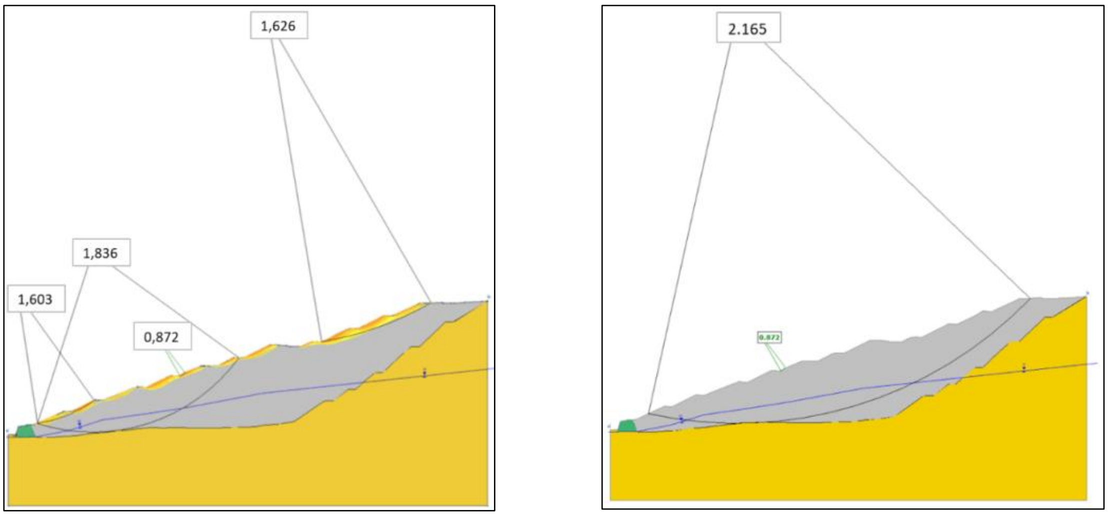
4.3 Stability analysis

This chapter collects the results obtained in the global stability of the landfill with industrial waste in different design situations. The safety factors were obtained using the Morgenstern-Price equilibrium limit method (1965) using the software Slide (Rockscience).

4.3.1 Normal design situation

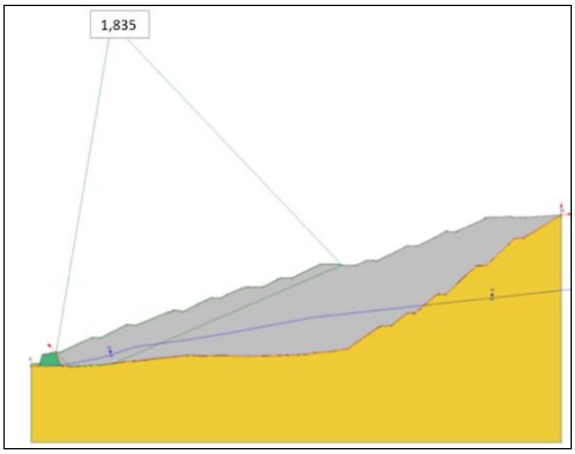
Figure 6 shows the stability analysis results for each sliding surface type for the normal design situation.

Different sliding surfaces are shown for sliding surfaces through the industrial wastes. The lowest safety factor (0.872) was obtained for a surface without significance, with only a shallow development. The safety factor obtained (1.603), for the other slightly deeper surfaces, is higher than the minimum required for this calculation (1.50). Finally, another sliding surface is analysed since it was considered the representative one of this study, with a safety factor of 1.836, also greater than required.



Sliding surface along industrial waste

Sliding surface passing along the landfill and the natural ground



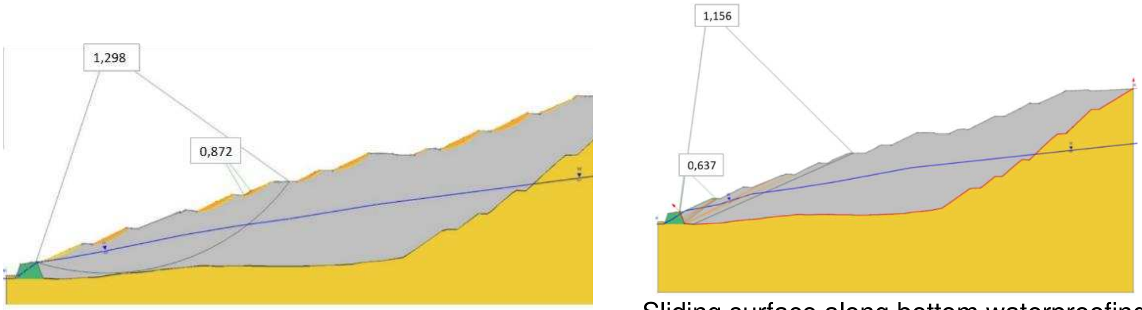
Sliding surface along bottom waterproofing package

Figure 6. *Results obtained for the normal design situation for each sliding surface analysed*

In the case of the analysis of the sliding surface along the bottom waterproofing package, the stability analysis results in a safety factor of 1.835 which is also higher than required (1.50). Finally, the stability calculation results for sliding surfaces along landfill and natural ground are also higher than 1.50 (2.165). It can be concluded that the modelled landfill is stable in the normal design situation.

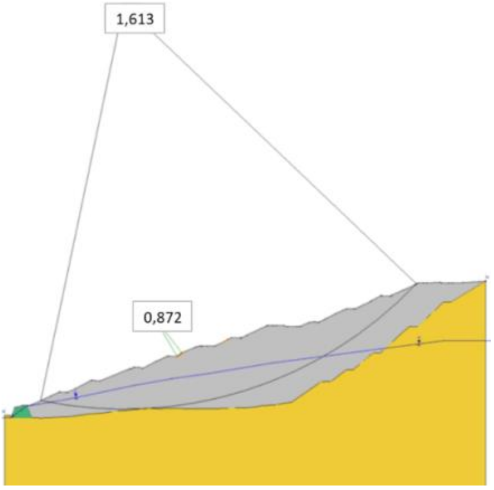
4.3.2 Accidental design situation

Figure 7 shows the stability analysis results for each sliding surface type for the accidental design situation.



Sliding surface along industrial waste

Sliding surface along bottom waterproofing package



Sliding surface passing along the landfill and the natural ground

Figure 7. *Results obtained for the accidental design situation for each sliding surface analysed*

For the stability analysis, the minimum safety factor required in the accidental design situation is 1.40 (see Table 3). This value is only reached for the sliding surface along the landfill and natural ground (1.613). Need to be highlighted that the low safety values obtained in the stability analysis (0.872 and 0.637) are considered not representative of any relevant sliding as they have only a shallow development. However, the safety values obtained for the sliding surfaces along the industrial waste and along the bottom waterproofing package are 1.298 and 1.156, respectively, less than required.

To solve this situation, another set of stability analyses was performed to determine the maximum leachate level, considered as piezometric level in the calculations, at which the required safety factor was obtained. These calculations were made both for the sliding surface along the industrial waste and along the bottom waterproofing package by raising the piezometric level, meter by meter, from the level set for the normal design situation. Figure 8 shows the values obtained in terms of the relation between the leaching level inside the industrial waste and the safety factor obtained for each type of sliding surfaces.

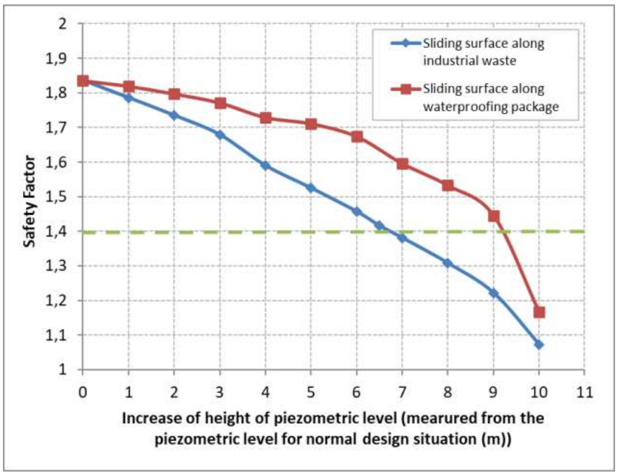


Figure 8. *Relation between the raise of the leaching level (measured from the normal design situation) and the safety factor obtained in stability analysis for sliding surfaces along industrial waste and bottom waterproofing package*

The analysis of the results collected in Figure 8 clearly shows the decrease of the global stability safety factor with the increase of the piezometric level. This fact highlights the relevance of the control of the piezometric level inside the landfill, something that is not always done due to the problems with the piezometer equipment provoked by the usual high temperatures of the wastes.

According to these calculations, for the sliding surface through the industrial waste, the leaching level inside the landfill could raise 6.5 m over the level of the normal design situation for the safety factor to be equal to the minimum safety factor required (1.40). Similarly, for sliding surface along the bottom waterproofing package, the minimum safety factor was reached when the leaching level was raised 9.4 m, so the other elevation is the one that drives the design. These values should be guaranteed during the landfill design life by monitoring the leachate elevations through piezometers installed in relevant places, mainly in the bottom part of the landfill, as noted before.

4.3.3 Extraordinary design situation

Figure 9 shows the stability analysis results for each sliding surface type for the extraordinary design situation. In this case, the only sliding surface to be analysed was through the bottom waterproofing package.

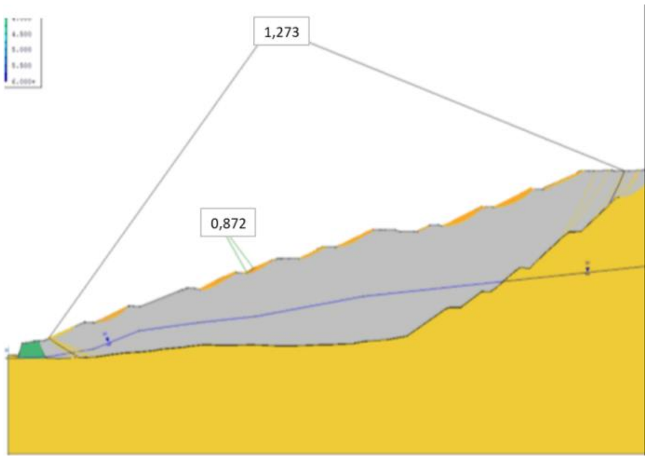


Figure 9. *Results obtained for the extraordinary design situation for the sliding surface along the bottom waterproofing package*

As shown in Figure 9, the global stability safety factor obtained in the calculation is 1.273, greater than the minimum required for this design situation (1.20), so the landfill can be considered stable in the extraordinary design situation, when a rupture of the bottom waterproofing package is modelled.

4.3.4 Summary of slope stability results

Table 4 shows the summary of stability results obtained in this study.

Table 4. *Summary of slope stability results*

Design situation	**Sliding surface**	**Safety Factor**
Normal	Industrial waste	1.836
	Bottom waterproofing package	2.165
	Landfill and natural ground	1.835
Accidental	Industrial waste	1.298
	Bottom waterproofing package	1.156
	Landfill and natural ground	1.613
Extraordinary	Bottom waterproofing package	1.273

5 CONCLUSIONS

The present work describes the procedure that should be followed to analyse the stability of a landfill for industrial wastes.

For this purpose, industrial waste resulting from automotive shredder residue (ASR) was described and tested in a large direct shear test (shear plane of 1x1 m) to obtain the strength properties to use in calculations. Following, the bases of design for the analysis of the global stability of landfills are described. According to that: a) four design situations should be studied: normal, accidental, extraordinary, and seismic; b) three sliding surfaces should be checked that develop along: the industrial waste, the landfill and the natural ground below, and the bottom waterproofing package; and c) the minimum global stability safety factor must be set for each design situation.

The work presents an example of a global stability analysis using these bases of design. Also, the maximum piezometric level (leachate level), inside the industrial waste that could be reached fulfilling the minimum safety factors to ensure the landfill is stable is determined. Due to the great influence of the piezometric level on the global stability of the landfill, the level of the leachates inside the landfill should be monitored during the landfill design life.

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