SLOPE STABILITY

LANDSLIDE AT S. PEDRO DE MOEL

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Abstract: On December 2017, the slope alongside the Aníbal Bettencourt street at S. Pedro de Moel unstablized, that resulted in a big landslide affecting the road and some walls of the builds nearby.

In the scope of the master's thesis the stability of the slope was studied, focusing on the several factors inherent to this analysis.

This thesis points out the São Pedro de Moel slope stability. Primarily the ground behaviour was analysed considering the soil site investigation. The soil parameters were studied by backanalysis and according to two different approaches, the limit equilibrium analysis and the finite element method. The evaluation of the factor of overall safety (FOS) was done through the two methods already mentioned using the software GeoSlope \ W (LEM) and Plaxis (FEM), considering the parameters accessed through FEM the results of FOS were compared and commented.

Once failure conditions were discovered, two interventions were presented with the purpose of restoring the slope stability. These solutions were analysed through FEM, designed and, finally, studied cost wise.

1. INTRODUCTION

São Pedro de Moel is a beach located in the Portugal Coastline, the development of this beach began at the end of the 19th century, currently, S. Pedro de Moel is visited essentially during the summer by tourists and inhabitants of the closest cities for holidays and leisure.

The development has led to the construction of vacations houses along the cliffs either for easier access to the beach or by the view, the places where they were built today can present considerable geotechnical risks, as it came to prove by the sliding of the Anibal Bettencourt's slope in December 2017.

It is important to analyze this type of situation to avoid material or personal damages. Nowadays there are already several methods of analysis for slope stability and for the verification of possible interventions, if proven necessary, these analyzes are inherent to geotechnical field. Throughout this document, the safety of the slope was assessed through two of those methods, the limit equilibrium method (LEM) and the finite element method (FEM), for further comparison.

2. THE ANIBAL BETTENCOURT SLOPE

2.1. THE EXISTING SITUATION AND PAST EVENTS

The area under study is located 400 meters from the beach of S. Pedro de Moel, is bordered by a residential area with typical houses, built in the 60s, 70s and 80s and at the foot of the slope an area of abandoned cultivation where the São Pedro river flows.

On December 10, 2017, the pipeline that supplies the water reservoir of S. Pedro de Moel collapse, this pipeline had a diameter of 20 centimeters and a pressure of 7 bar, which upon burst caused the area to flood. The accumulation of water at the top of the slope, together with the speed of the water, caused it to rise up the road and seep through the hillside (Ferreira, et al., 2018).

FIGURE 1- WATER FLOW WITH LOCATION OF LANDSLIDE, WATER RESERVOIR AND RUPTURED PIPELINE (FERREIRA, ET AL., 2018)

The flow of water led to the erosion and transport of the sand layer, since the pipeline was active until the next morning, the erosion process became worse until discovered the next day, when there was already a ravine of 30 meters wide and 9 meters deep. The result of the erosion is visible along the water course where there are several wrecks of the road, the walkway and the walls, these follow along the valley of S. Pedro where two accumulation cones of material, next to the existing water line were formed

The town Hall of Marinha Grande started on the morning of December 11, provisional stabilization works for the slope. The solution consisted in filling the sidehill with pebbles and by a surface of compacted of granular material.
The embankment was protected by a network also to interdict the passage of vehicles, the essential infrastructure like the sewage pipes, the water and electricity supply were reestablished.

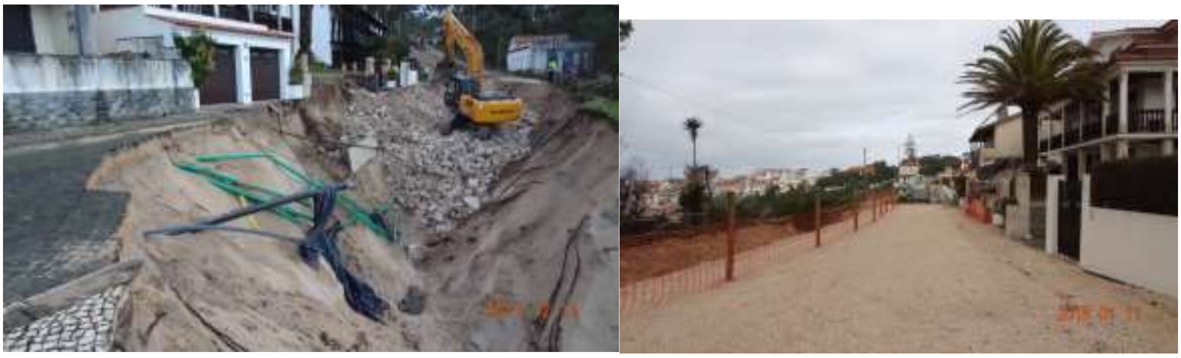


FIGURE 2- EXECUTION OF THE TEMPORARY WORKS AND THE FINAL RESULT (FERREIRA, ET AL., 2018)

There have been records of similar events in this area of the embankment in the years 2002, 2016 and 2017, all these due to excessive water runoff. In the year of 2002 the accumulation of water was the result of a sudden intense precipitation that caused the rupture of a pipeline, in 2016 the sliding was also provoked by strong precipitation. On both occasions the solution founded consisted in filling the slope with high granulometric material. Along the slope it was also possible to see the occasional areas of shallow landslides and the collapse of small trees.

2.2. GROUND CHARACTERIZATION

A geotechnical study was requested from the University of Coimbra, which carried out two distinct test trials, one DPSH test and one georadar test. Through these two, and the information provided through the geological map and altimetric maps it was possible to build a geotechnical model and assign resistant parameters to the various layers.

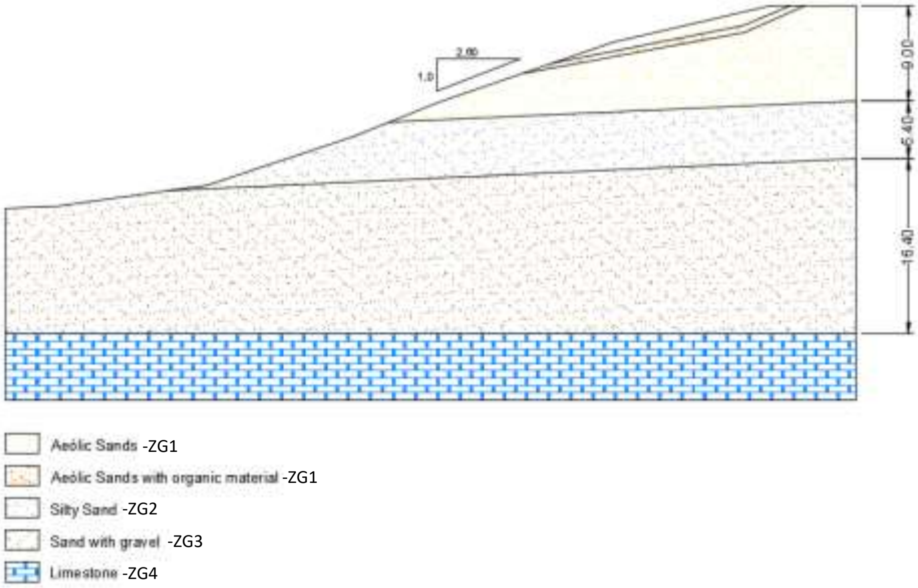


FIGURE 3- SLOPE CROSS SECTION AND GEOLOGICAL PROFILE

In Table 1 is presented the average number of strokes obtained through a correlation with SPT for each layer.

TABLE 1- GEOTECNHICAL PARAMETERS BASED ON THE SPT STROKES

Lithology	Z(m)	N_{spt}	$\phi'(°)$	$c'(kPa)$
ZG1	0-9,0	9	30-35	0
ZG2	9,0-14,4	28	35-40	10
ZG3	14,4-30,8	54	40-45	10
ZG4	30,8-	-	>45	400

3. STABILITY ANALYSIS

The slopes when subjected to actions and geotechnical changes can unstablize, this results in mass displacement in the downward direction where gravity plays a fundamental role.

In this frame, an analysis was carried out through two different methods. The first method was the limit equilibrium (LEM) in which a comparison between the resistant and the action forces and moments in a sliding surface was made.

Since the movement of the soil occurred mainly in the transversal direction of the slope, and considering that the longitudinal dimension of the slope is much bigger than the transversal dimensions, the cross-section represents a transversal profile with a layer distribution similar to Figure 3

3.1. THE LIMIT EQUILIBRIUM METHOD (LEM)

Within the equilibrium analysis there are several methods, the most used being the slice method, which consists in dividing the mass of soil that lies inside the sliding surface into several vertical portions. The method of slices demands the evaluation of the values of tangential force and normal force of each slice to later check if the result of the sum of all the slices is enough to respond safely to the requested loads, that is, FoS with value greater than or equal to one.

For this analysis the Morgenstern-Prince method was used since it is suitable for several slip surfaces, satisfies the equilibrium of moments and forces and counts the interaction between normal (X) and tangential (E) forces between slices independently of the resultant X/E.

In this model, the vertical and horizontal displacements were blocked at the base of the slope, at the lateral borders only the horizontal displacements were restricted and at the surface of the slope the displacements were not conditioned in any direction. That said, and before the beginning of backanalysis, the loads of houses and road were applied, $5kN/m^2$and $26kN/m^2$ respectively.

The backanalysis allow the calibration of the soil parameters prior to collapse, thus, starting from the values mentioned in Table 1, an iterative process started until a unit value for the factor of overall safety was reached. This analysis was carried out for the most unfavorable case, with the high-groundwater level, then the soil cohesion and the friction angle were changed and the values that led to a sliding surface similar to the one observed at the site were adopted.

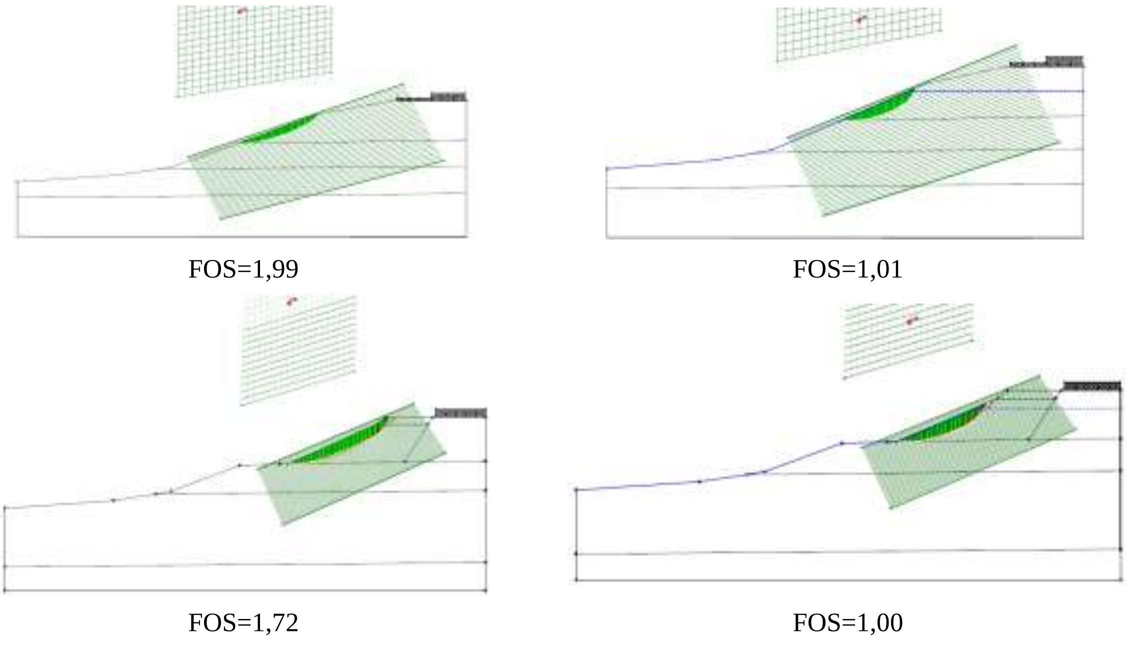
After checking the soil parameters, it was necessary to understand the characteristics of the materials used in the emergency solution, to do so, a similar approach to the previous one was used, however in this modeling, the interaction of the road's load wasn't since it is considered closed. The adopted geotechnical parameters are shown in Table 2.

TABLE 2- SOIL PARAMETERS OBTAID BY RETROANALYSIS (*GEOSLOPE\W*)

Mohr-Coulomb Model

Parameters		ZG1	ZG2	ZG3	Gravel	Sand
General properties	Behaviour	Drained	Drained	Drained	Drained	Drained
	$\gamma\_sat\ (kN/m^3)$	18	21	22	21	22
Strength Parameters	$\phi'(°)$	30	35	40	32	35
	$c'(kPa)$	1,5	10	10	1,5	10

Once established the soil parameters, several stability analyses were carried out, two for the natural slope, with a high-groundwater level and a low groundwater level, and then the emergency intervention was analyzed for the same conditions. The values of the overall factor of overall safety and the sliding surface are showed in Figure 4.



FOS=1,99 FOS=1,01

FOS=1,72 FOS=1,00

FIGURE 4- FACTOR OF OVERALL SAFETY OBTAINED WITH GEOSLOPE\W

3.2. THE FINITE ELEMENT METHOD (FEM)

Due to its advantages, the finite element method is currently the most used method, the great difference between the FEM and the LEM is the ability of the first one to relate stresses with deformations, which allows to estimate the deformations that a certain element suffers when requested to a change stress. The study of the factor of overall safety was carried out using the PHI-C reduction method, in this method, the Plaxis software iteratively decreases the value of cohesion and the angle of friction until convergence is reached, the relation between the initial values of resistance and those that led to the collapse led to the factor of overall safety.

Plaxis allows the user to choose from a wide variety of models, choosing the right constitutive model is very important so that the soil behavior is as close to the real as possible. Among the several models available, the hardening soil model was adopted, this one is suitable for granular soils and was adopted for all ground layers.

The Hardening Soil model (H-S), is an elastoplastic model with hardening, this is characterized by allowing plastic deformations prior to rupture. In this model the yield surface is not unique, it is a function of the stress of the material and its stiffness (k) (Freitas, 2017).

This model does not allow a state of stresses outside the yield surface, but it may expand or contract as the material hardens or softens respectively to accommodate a new state of stress.

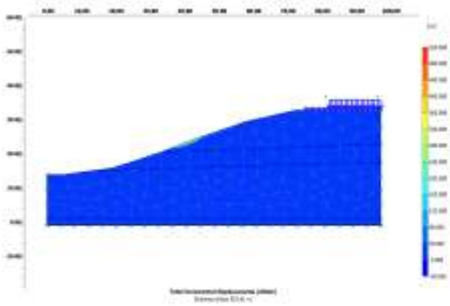
The H-S model uses the Mohr-Coulomb failure criterion, this criterion relates the shear stress to the normal stress through the soil parameters: cohesion c, friction angle ϕ and dilatancy angle ψ.

Once again, the soil parameters obtained by backanalysis are presented in Table 3.

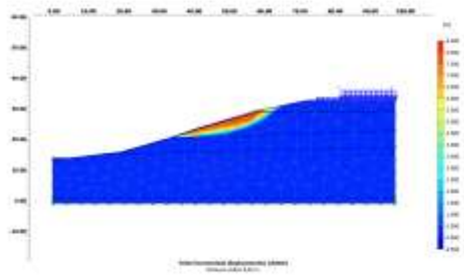
TABLE 3-GROUND PARAMETERS OBTAINED BY BACKANALYSIS (*PLAXIS*)

Parameters		Units	Aeolic Sand	Silty Sandy	Sand with Gravel	Limestone	Sand (SW)	Gravel (GW)
Behaviour		-	Drained	Drained	Drained	Drained	Drained	Drained
γ_{hum}		kN/m^3	18,0	21,0	22,0	25,0	19	20
γ_{sat}		kN/m^3	19,0	22,0	22,0	26,0	21	20
Strength	c	kN/m^2	2,0	10	10	40	15	2,0
	ϕ	°	30	35	40	0	40	32
	ψ	°	0	0	0	0,9	0	0
	Rf	-	0,9	0,9	0,9	-	0,9	0,9
Stiffness	E_{50}^{ref}	MPa	10	13	70	400	30	80
	E_{oed}^{ref}	MPa	10	13	70	397	30	80
	E_{ur}^{ref}	MPa	30	39	210	1200	90	240
	m	-	0,5	0,5	0,5	0,5	0,5	0,5
	ν_{ur}	-	0,2	0,2	0,2	0,2	0,2	0,2
	p_{ref}	kN/m^2	100	100	100	100	100	100
	K_0^{NC}	-	0,5	0,426	0,357	0,357	0,357	0,357

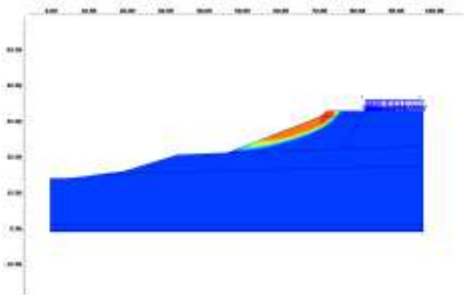
As for the LEM analysis, the slope was studied before collapse and as it is currently found, both for different groundwater level situations. The sliding surface is shown in Figure 5, as it’s the FoS.



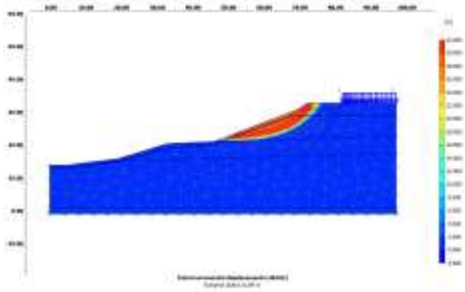
FOS=1,86



FOS=1,04



FOS=1,66



FOS=1,05

FIGURE 5- FACTOR OF OVERALL SAFETY ACCORDING TO PLAXIS

3.3. *Result comparison*

The main difference between the two methods is that the LEM is a static analysis, while the finite element method uses a constitutive relation that relates stress-strain. Since the FEM has the capacity to reproduce the soil behavior, the parameters obtained through the backanalysis in FEM are used in the LEM so that a viable comparison between the methods can be made. The results obtained are in Figure 6.

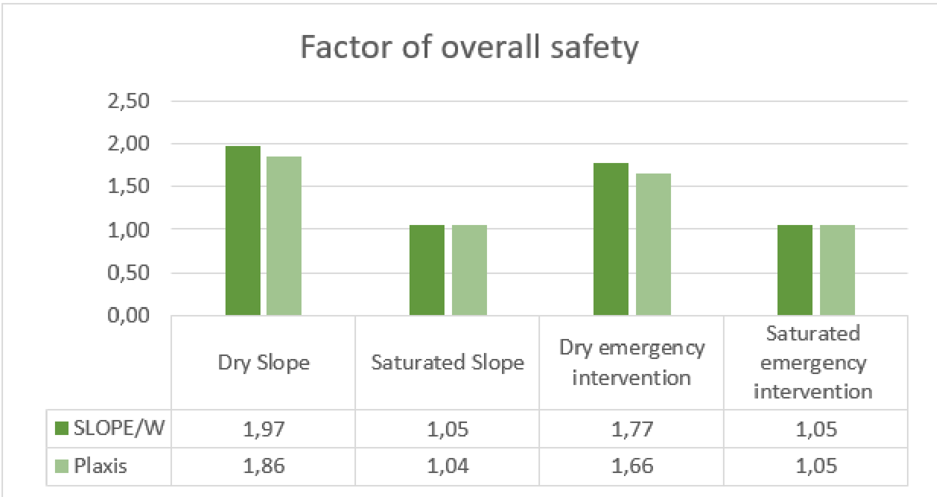


FIGURE 6-FACTOR OF OVERALL SAFETY COMPARISON BETWEEN THE TWO METHODS

It is noteworthy that during the various simulations, the soil parameters obtained were higher than expected, especially the value of cohesion for materials such as gravel and eolic sand. It is also important to note that a FoS equal to 1 in this simulation is not a value that indicates slope safety, since the FoS equal to one indicates less prone to collapse when the safety factors according to EC7 are applied, which has not happened in this case. So that conclude that it will be necessary to design an alternative solution to the existing one in order to restore the safety of the slope.

It should again be pointed out that, analysis through the FEM it is possible to study the stress-strain interaction, which is not possible to study in the LEM, which means this method is advised for the study complex geotechnical scenarios. However, as the analysis through the equilibrium limit method is quite fast and easy to analyze, this method has been used for many years and due to its simplicity and because it leads to fairly good preliminary approaches of FOS.

4. Stabilization Solutions

As already mentioned, the stabilization works done in 2002 and 2016 were not adequate once the slope collapsed when the water table rose. The most recent intervention was executed immediately after the collapse and, from the previous analyzes, the slope is stable only for the low groundwater level therefor, to restore the slope stability, two solutions were suggested and studied.

4.1. Concrete wall and micropiles

The first solution proposed to stabilize the slope is a concrete wall founded on micropiles with the back of the wall filled with light weight aggregates, thus ensuring a good drainage of the slope and small earth pressures on the wall.

Among the various advantages of micropiles, are mentioned bellow and considered fundamental for this case:.

- Execution in confined spaces;
- Possibility to accommodate tension loads;
- Excellent settlements control;
- Low ground disturbance;
- Possibility of execution of inclined elements, with great resistance to horizontal forces.

For this solution two alignments of micropiles were considered, one vertical and the other with an inclination of 30º, these works as a foundation of the wall and spaced 50 centimeters apart.

4.1.1. Numerical modeling

For the simulation of this solution, it was necessary to characterize the materials used according to the models in Plaxis software and to define the various calculation steps. The materials used in this solution were the micropiles, the lightweight aggregates and the concrete wall, the geometry of the solution as shown in Figure 7.

During the calculation phases, the lowest FoS value was obtained when the landfill was removed, FoS = 1.17, however, when the solution was complete it presents a FoS higher than 3,50 for a high-water table.

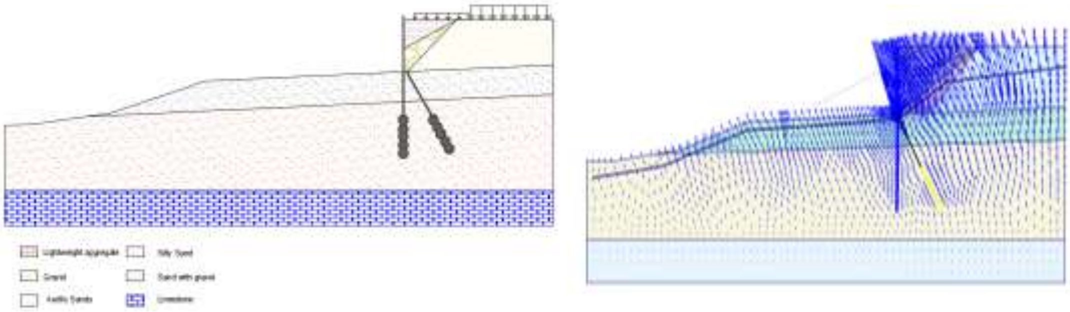


FIGURE 7- GEOMETRY OF THE CONCRETE WALL AND MICROPILES SOLUTION AND DEFORMATION FOR HIGH GROUND WATER LEVEL

Since safety coefficients were not applied to the soil parameters or applied loads, it is assumed that FoS above 1.5 will ensure the allowable safety of the solution.

For these solutions the boundaries conditions were maintained in the same position for the displacements analysis, these conditions influence the horizontal displacement, however, since the displacements are small this choice doesn't invalidate the deformations analysis.

Considering the surrounding constructions, it was important that the displacements didn't exceed the 50mm in that area. In this solution, the maximum accumulated displacement was inferior to 10cm and near the construction it didn't exceed the 2,50cm. The development of the deformations during the several phases are presented in Figure 8.

According to the obtained results it is proved that the solution meets the safety and the deformation criteria.

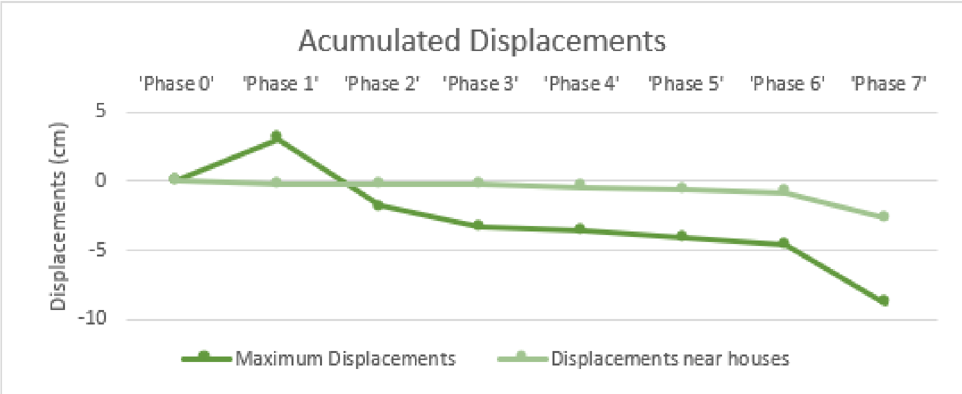


FIGURE 8- SETTLEMENTS EVOLUTION THROUGH MAIN CALCULATION PHASES

4.2. BORED PILE WALL

The second proposed solution was the execution of a bored pile wall. This solution is indicated for zones with high water table (cause of collapse) and for urban zones since this solution does not introduce great deformations in the ground. Within the various methods, the piles executed using the recovered casing was chosen, this is suitable for soils with low cohesion and with a high index of voids, as in this case. Of the various advantages of bored piles, the following stand out:

- Can be executed in limited spaces and difficult to access;
- Have a good resistance and low deformation;
- The soil confinement is kept.

For this case, the solution consists of secant bored piles of 800 mm with a spacing of 650 mm, with reinforced and poor concrete pile of the same diameter the are coated with concrete to minimize the visual impact.

4.2.1. NUMERICAL MODELING

The constructive process of this solution begins with execution of the bored piles, excavation of the existing landfill and later filling it with lightweight aggregates. In each calculation phase, the factor of overall safety and the soil deformations suffered by the soil were analyzed.

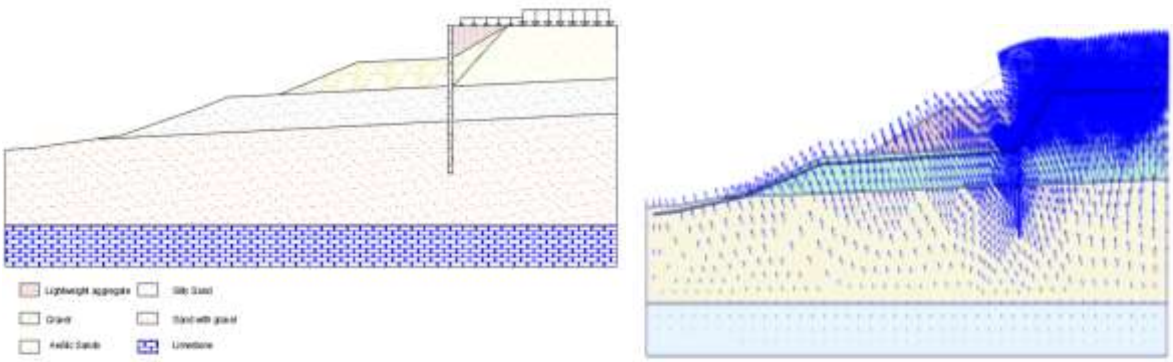


FIGURE 9- GEOMETRY OF THE PILEWALL AND DEFORMATIONS FOR HIGH GROUND WATER LEVEL

During the construction process the minimum FoS obtained was 1,66 during the execution of the piles and when the water table rises the FoS is 1.88. This concludes that the construction of the pile curtain ensures the safety of workers and users of the road and houses.

Nevertheless, it was still necessary to analyze the soil deformations, during the execution of this solution, which, by analyzing the Figure 10, guarantees the integrity of the buildings. In comparison with the solution presented before, this one induces less deformations.

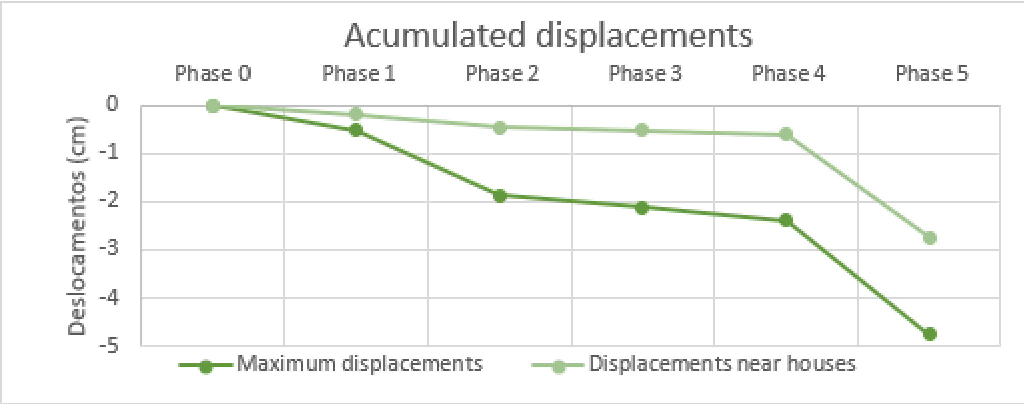


FIGURE 10- SETTLEMENTS EVOLUTION THROUGH MAIN CALCULATION PHASES

5. Solution comparison

Prior to the economic analysis of the proposed solutions, a cost estimate was made for the previous interventions of 2002 and 2016.

The instability that occurred in 2002 interdicted access to the road that also collapsed. For this solution, it was necessary to fill the slope, to rebuild part of the road that collapsed and to construct new drainage devices.

It should be noted that the damages recorded in the telecommunications or electrical infrastructures were not considered, these can have high costs but due to the lack of data these were omitted.

The solution found was not safe and the cost inherent to it eventually became a loss when in 2016 the slope collapsed again.

After the occurrence in 2016, solution found consisted in filling the slope with drainage material being that this was secured with wood piles made that also had a stabilizing function in the slope.

However, the two interventions proved to be insufficient and in 2017 the third slip occurred, as analysed throughout this thesis. The landslide that occurred in December was the one that caused the most damage, and reached a house that needed minor repairs, these costs are included in Table 4.

TABLE 4- ESTIMATE COSTS OF THE VARIOUS SOLUTIONS

	Cost
Intervention 2002	9527,40 €
Intervention 2016	4477,20 €
Emergency intervention (2017)	48075,00 €
Total	**62079,60 €**

Considering the scenario of instability generated after the slope collapse, the emergency solution, given its speed of execution, was the indicated choice for immediate repair of the embankment, however, this was not a long-term solution, so that were proposed two alternative solutions whose cost were evaluated.

For both solutions it was foreseen the improvement of the slope, its transport to dump and execution of the pavements, nevertheless each solution had its structural elements that lead to a slight difference between the two solutions. Both proposed solutions result in a value well above the cost of the previous interventions, however they guarantee a higher FoS for a higher design life period.

The first solution with concrete wall and micropiles has an approximate cost of 198 978.00€. The solution constituted by the pile curtain has a slightly lower value of 185 084,00 €, however it has the disadvantage of being very aggressive visually.

TABLE 5- ESTIMATE COST FOR THE PROPOSED SOLUTIONS

	Total cost
Solution 1	198.978,00 €
Solution 2	185.084,00 €

Although there is a large discrepancy between the proposed solutions and the cost of the interventions already carried out in the slope, the difference may decrease in the case of a new landslide, because as mentioned the slope to a high-ground water level may unstablize, leading to a volume of mobilized soil higher than in previous events.

It should be noted that the two solutions can be studied to optimize them, this optimization leads to a decrease cost wise. It is also important to note that only two possible solutions have been presented to solve the problem, however it is possible that there are other solutions and technologies that could interesting and able to restore the slope stability and competitive when compared to the presented solutions.

6. MAIN CCONCLUSIONS AND FUTURE WORKS

In the first stage of the analysis of the case study of Rua Aníbal Bettencourt, the reports available by CMMG – Câmara Munincipal da Marinha Grande were analyzed, despite the scarce field tests, it was possible to build a structural model through the photographic registers after the incident. Thus, the first conclusion to be drawn is the importance that a correct characterization, although there are always uncertainties, these doubts can be reduced the better the characterization.

After constructing the model with the two software, the hypothesis created initially, both through the limit equilibrium and the finite element method, was confirmed by the increase in the ground water level the slope becomes unstable. A simulation of the emergency intervention was carried out, which lead to the conclusion that, for a situation similar to that of December 2017, the likelihood of the slope collapsing again is very high.

Two solutions were proposed to restore slope stability and a brief analysis of the economic impact of the solutions was made. Although the value of the proposed interventions has proved to be high in the event that an adequate solution is not made, the cost of the provisory solutions may be higher than the cost of the proposed solutions.

From this work it must be withheld that, as already mentioned, the execution of ground site investigation, as soon as a landslide occurs it is fundamental to realize which type of soil will be intervened and the cause of instability.

It is also suggested that a stability analysis of the entire slope be performed that should also contain a dynamic analysis, to measure the sensitivity of the emergency solution to seismic action.

As the instability occurred due to the increase in the ground water table, this consequence of a rupture of pipes, it is advisable to check the supply and drainage systems of the S. Pedro de Moel area in order to adapt the pipelines to the requirements of the zone and to preventively repair pipes that are damaged.

Finally, it should be pointed out that, when there are geotechnical risk stabilization measures should be preventive and not reactive as in most cases.

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