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Analysis and Remedies for Landslides Including Vegetation: A Case Study in Lebanon

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Abstract: This paper aims to study and analyze the instability of slopes, their causes and possible remedies. The studied slope is located in Lebanon, and it is regularly subjected to slope instability in the rainfall season. Based on different boreholes results for the same site, two models were modeled using Plaxis and Talren, they were both studied under the effect of water, excavation and seismic load. The results show that the water is a principle cause of slope instability, by decreasing the shear parameters of soil or by the inducing pore pressure due to running water between layers. Many remedies were applied, and their results were analyzed and studied. Soil reinforcements, nails and piles, were applied and as water content increased, the number of reinforcement needed was high. Vegetation and drainage are more efficient when it comes to water problems. Both vegetation and drainage were modeled and the number of needed reinforcement decreased significantly assuring their advantages alongside with the reduction of the remedy price and being environmental friendly.

Keywords: Soil, Slope Stability, Safety Factor, Failure Surface, Piles, Nails, Vegetation

1. Introduction

Stability analysis of earth slopes is one of the fundamental calculations in geotechnical engineering. Many calculation methods and remedies have been used until now. Two main approaches are applied in slope stability analysis: Deterministic method [1] and Limit Equilibrium Methods (LEM). Fellenius [2] introduced the Ordinary or Swedish method of slices in the mid-1950s. Janbu [3] and Bishop [4] presented some improvements in this method. Bishop included inter-slice normal forces, but ignored the inter-slice shear forces. Bishop's simplified method satisfies only moment equilibrium, whereas Janbu's simplified method takes into consideration only horizontal force equilibrium. The development of numerical modeling has allowed the evolution of iterative methods, such as Morgenstern and Price [5] or Spencer [6], and the implementation of these approaches into computer softwares (Geo-Slope international). Consequently, it is possible to conduct iterative calculations allowing the inclusion of both inter-slice and equilibrium equations.

Numerical simulations are used to overcome the limitations of limit equilibrium methods which include strain-displacement procedures. Several numerical methods are gaining increasing popularity in slope stability engineering due to calculation of the safety factor calculations in an efficient way [7, 8]. The shear strength reduction technique (SSR) starts to be a very popular numerical method for slope stability. The c-φ reduction method is based on the reduction of the cohesion (c) and the tangent of the friction angle (tan φ) of the soil. These parameters are reduced in steps until the soil mass fails [9, 10]. A modified shear strength reduction technique (MSSR) was developed. It is based on reducing soils' shear properties after identification of the first slip surface. The use of MSSR has some serious advantages over LEM calculation being more sensitive [9].

The Random Finite Element Method (RFEM) is an advanced probabilistic approach that combines elasto-plastic finite element analysis with random field theory generated using the Local Average Subdivision Method [11]. It was able to take full account of spatial correlation and local averaging, and observe their impact on the probability of failure using a parametric approach [12].

Different slope stabilization techniques can be applied and some remedies are usually used such as piles to stabilize or recover collapsed slopes [13, 14, 15]. Nails are used to improve the shear strength of soil [16, 17, 18]. Drainage trenches are used to lower the groundwater level increasing the slope stability especially during the rainfall season [19, 20]. Recently, some researches have proposed the study of the vegetation effect on the slope stability; the studies highlighted the importance of the vegetation as a solution for landslides issues [21, 22, 23, 24, 25, 26]

In this paper, we studied a slope stability model using numerical modeling. The techniques mentioned above will be considered and modeled. The soil mechanical properties of the slope are determined from the in-situ and laboratory tests. We studied the stability of an existing slope in Lebanon, which has collapsed due to an excavation during the rainfall season. Slope stability analysis is conducted by taking into account the factors affecting its stability and the resisting techniques that help maintaining its stability.

2. Site Description

The slope is located in Namliyeh, Mont-Lebanon, between Dahr Al Baydar and Chtoura in Lebanon. This slope is subjected to a failure during the rainfall season. Two boreholes were drilled at this location; where in-situ Standard Penetration Test SPT was performed every 1.5 m. Soil samples were also taken from these boreholes to be tested in the laboratory. The borehole N°1 shows the existence of two main layers, a marl layer from the top surface to a depth of 7 m, and a limestone layer from the depth of 7 m to the end of borehole. Table 1 shows the mechanical parameters of layers of the slope as obtained by laboratory tests or by using the SPT correlations.

Table 1. *Model 1 Soil Layers Mechanical Properties.*

Layer	Nature of soil	Depth (m)	E (kPa)	c (kPa)	ϕ (°)
1	Marl	0-7	8500	31.4	17.5
2	Limestone	>7	200000	243.3	17.5

In addition to other parameters, the volumetric unsaturated weight γ_{unsat} is equal to 18 kN/m^3 and poisson's ratio ν is set 0.3 for both layers, while the volumetric saturated weight γ_{sat} is equal to 20 kN/m^3 for layer 1 and 19 kN/m^3 for layer 2.

The borehole N°2 shows the existence of four main layers, the first one is a clay layer of 5 m thickness, the second is a medium sand layer of 2 m thickness, and dense sand between 7m and 12m depth, and finally a limestone layer from the depth of 12m to the end of borehole. Table 2 summarizes the mechanical parameters of slope's soil layers.

Table 2. *Model 2 Soil Layers Mechanical Properties.*

Layer	Nature of soil	Depth (m)	E (kPa)	SPT	c (kPa)	ϕ (°)
1	Clay	0-5	5000	10	30	15
2	Sand	5-7	4000	11	5	28
3	Dense Sand	7-12	9000	26	18	30
4	Marlstone	>12	200000	-	150	18

In addition to other parameters, the volumetric unsaturated weight γ_{unsat} is equal to 18 kN/m^3 and poisson's ratio ν is set 0.3 for all layers, while the volumetric saturated weight γ_{sat} is equal to 20 kN/m^3 for layers 1, 2 and 3 and 19 kN/m^3 for layer 4.

3. Stability Analysis

The study of slope stability is based on the c-phi reduction method. This method is based on the incremental displacements until failure, where the final step (at failure) gives an indication of the likely failure mechanism. Two models were simulated using Plaxis software.

3.1. Initial State

The slope is considered in its natural state, where the failure surface of the initial slope is almost planar for both models as shown in Figures 1 and 2. The slope is stable with safety factor, SF, equals to 2.43 for model 1 and 2.31 for model 2.

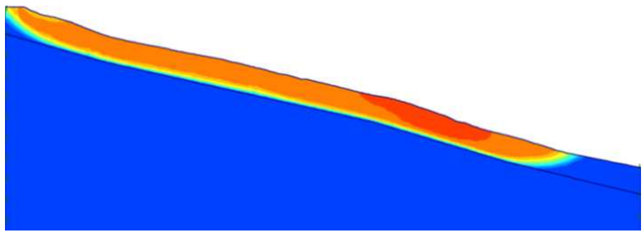

Figure 1. *Failure Surface of Model 1, SF=2.43.*

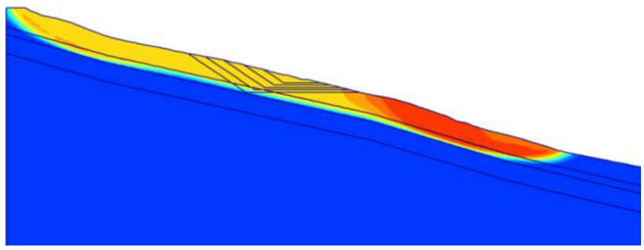

Figure 2. *Failure Surface of Model 2, SF=2.31.*

3.2. Influence of an Excavation

This slope is highly subjected to a manmade road excavation. The modeled road excavation can be of different widths and depths with a slope angle of 3H:2V. The results for both models are shown in table 3, where the safety factor is acceptable (SF>1.5) in almost all cases. The slope remains stable, therefore, the excavation is not the main cause of landslide here but it might be a contributing factor. Figures 3 and 4 show the failure surface for both models which is circular due to the existence of excavation.

Table 3. *Variation of Safety Factor with Different Excavation's Depths.*

Excavation		Safety Factor Static	
Width (m)	**Depth (m)**	**Model 1**	**Model 2**
0	0	2.436	2.306
10	3.513	2.431	2.290
15	5.388	2.400	2.251
20	7.274	2.227	1.837
25	8.831	2.036	1.514
30	10.3	2.045	1.421

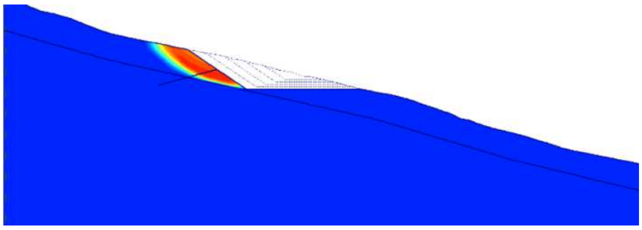

Figure 3. *Failure Surface of Model 1 After 10.3 m Excavation's Depth.*

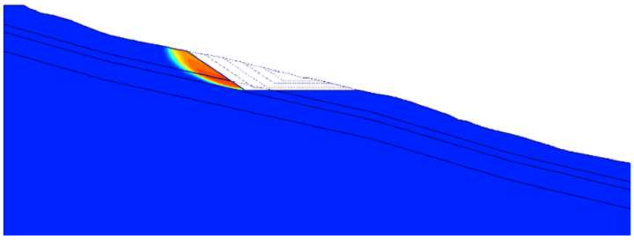

Figure 4. *Failure Surface of Model 2 After 10.3 m Excavation's Depth.*

3.3. Activation of Seismic Load

The seismic analysis is conducted by applying a seismic load with acceleration a=0.2g. The results for both models are shown in table 4 below, where the slope remains stable in all cases except one particular case in the 10.3 m excavation's depth in model 2.

Table 4. *Seismic Load, Variation of Safety Factor with Different Excavation's Depths.*

Excavation	Safety Factor Seismic	
Depth (m)	**Model 1**	**Model 2**
0	1.321	1.174
3.513	1.340	1.182
5.388	1.350	1.174
7.274	1.303	1.129
8.831	1.264	1.017
10.3	1.250	Body collapses

4. Effect of Water on Slope Stability

4.1. Influence of Water Content on Shear Parameters

When it rains, water falling on the surface of the soil will either infiltrate into the soil or run off along the surface. Part of the water that infiltrates into the soil will be absorbed by the upper soil layers leading to the loss of the mechanical properties of the layer.

Concerning the slope stability, it is highly affected by the increase of soil water content. Initially, the slope's water content is 15%. In rainfall season, it may increase to 18%, 20%, 22% and maybe 25%. The shear strength of soil is characterized by the cohesion (c) and the friction angle (φ). It was proven that the shear strength parameters (c, φ), for cohesive soils, decrease with the increase of moisture content w [27, 28, 29]. Whereas for sand, it was shown that for granular soil with low clay quantity, the cohesion and the angle of internal friction almost do not vary with the increase of water content [30].

The figures below show the variation of the cohesion and the internal friction angle with the increase of water content of sandy clay [27].

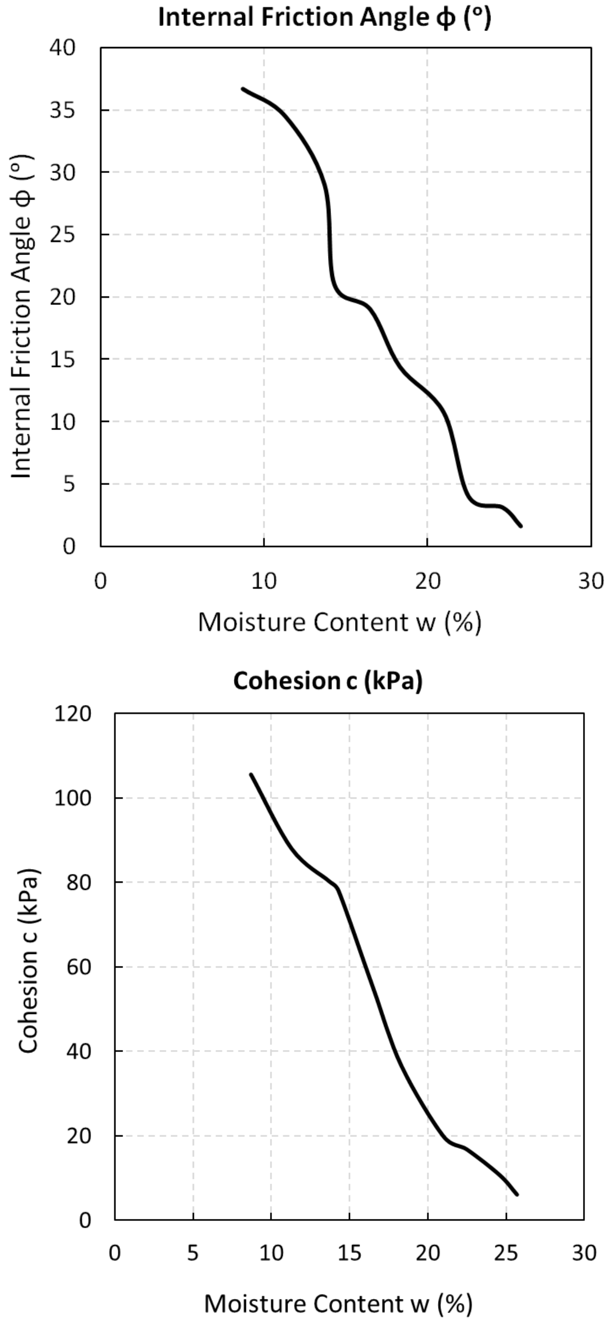

Figure 5. *Variation of Shear Parameters as a Function of Moisture Content [27].*

***Table 5.** Shear Parameters of Marl and Clay Based on Different Water Contents.*

Water Content	Marl, Model 1		Clay, Model 2	
w (%)	ϕ (°)	c (kPa)	ϕ (°)	c (kPa)
15	17.5	31.4	15	30
18	13.1	17.4	11.3	16.6
20	10.5	11.1	9	10.6
22	5	7.8	4.3	7.5
25	2.2	4	1.9	3.8

Using the graphs shown in Figure 5, we can estimate the new shear parameters for marl (Model 1) and clay (Model 2) based on the decrease rate of cohesion and angle of internal friction with the increase of water content. The new shear parameters are shown in table 5, and figure 6 shows the variation of the safety factor as a function of water content.

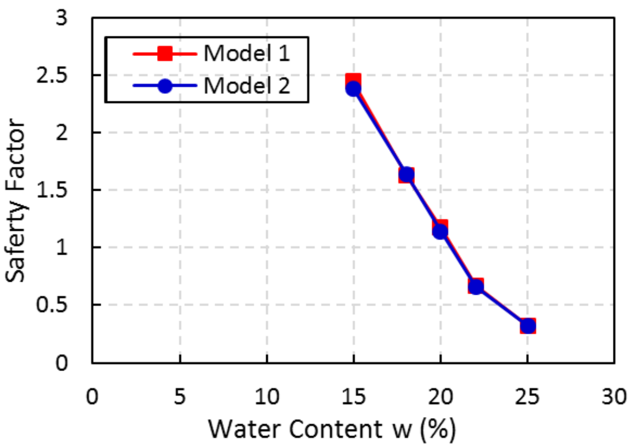

***Figure 6.** Variation of SF as a Function of Water Content.*

Based on those results, the failure is reached (SF<1.5) as the water content increases reaching a value between 18% and 20%.

4.2. Influence of Excavation and Seismic Load

The influence of an excavation and seismic loads is studied taking into account more specific cases of water content between 18% and 20%. From the results of table 6, it is obvious that the slope for w=18% is unstable in all cases after the activation of the seismic load. In the static case, when the excavation's depth increases, the safety factor decreases reaching failure. The slope for w=20% is already unstable before the application of the excavation and seismic load. The analysis of the results shows that the main cause of failure here is the increase in water content which decreases the shear parameters of marl and clay, and the application of excavation and seismic load are contributing factors in the slope instability.

***Table 6.** Safety Factor with Excavation and Seismic Load.*

w=18%	Model 1		Model 2	
Excavation's depth (m)	SF Static	SF Seismic	SF Static	SF Seismic
0	1.568	Failure	1.620	Failure
3.5	1.564	Failure	1.620	Failure
5.4	1.543	Failure	1.482	Failure
7.3	1.394	Failure	1.349	Failure
8.8	1.267	Failure	1.251	Failure
10.3	1.250	Failure	1.194	Failure

4.3. Influence of Running Water on Slope Stability

The pore pressure that comes from the running water between layers can be developed due to the rising of water table or a downstream water flow.

Using Talren software, we were able to study the effect of the running water on the surface of the impermeable layer by computing the safety factor and analyzing the slope stability for both models. Different models with different pore pressures from 0 to 100 kPa along the failure surface have been studied.

From figure 7, it is obvious that the inserted pore pressure has a great effect on the safety factor and thus the stability of the slope. For both models, static and seismic cases, the safety factor decreases about 40 to 45% with an increasing pore pressure from 0 to 100 kPa along the failure surface between the 2 layers.

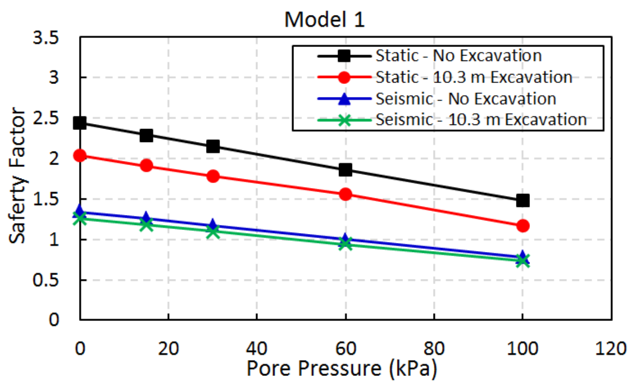

***Figure 7.** Model 1, Effect of Pore Pressure on Safety Factor.*

5. Remedies

5.1. Soil Reinforcement

5.1.1. Nails

The steel nails used in this study are inclined 15°, spaced 2 m with diameter of 15 cm, a length of 16 m, a normal stiffness EA=1.77×10^6 kN/m and a flexural rigidity EI=2.50×10^3 kN.m^2/m. Figures 8 and 11 summarize the needed number of nail rows to stabilize the slope for both models. The number of nail rows increases with the increase of both excavation's depth and water content. Figures 9, 10, 12 and 13 illustrate the location of applied nails on both models.

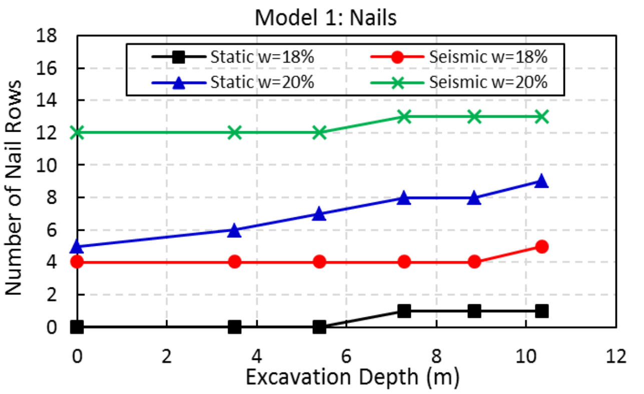

Figure 8. *Model 1, Variation of Number of Nail Rows with the Variation of Excavation's Depth and Water Content.*

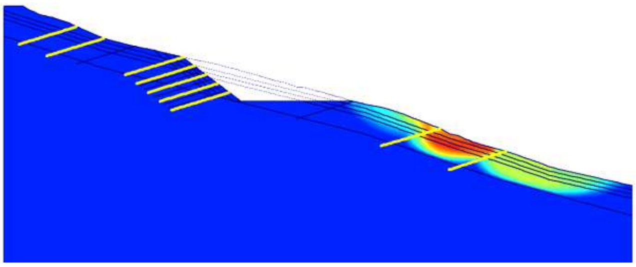

Figure 9. *Model 1, Static, 10.3 m Excavation, w=20%.*

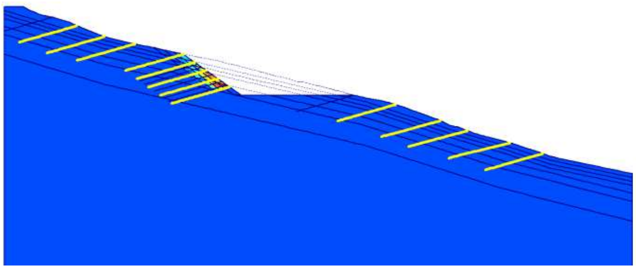

Figure 10. *Model 1, Seismic, 10.3 m Excavation, w=20%.*

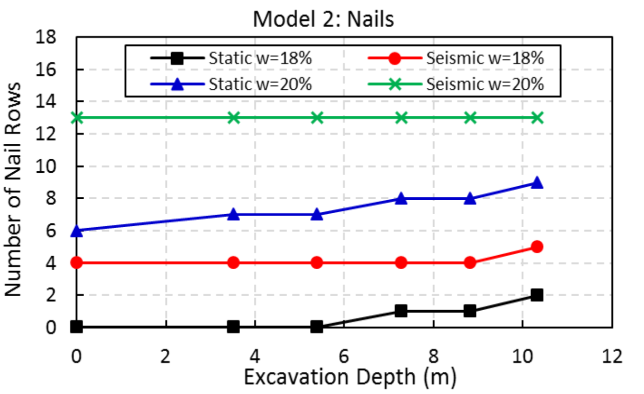

Figure 11. *Model 2, Variation of Number of Nail Rows with the Variation of Excavation's Depth and Water Content.*

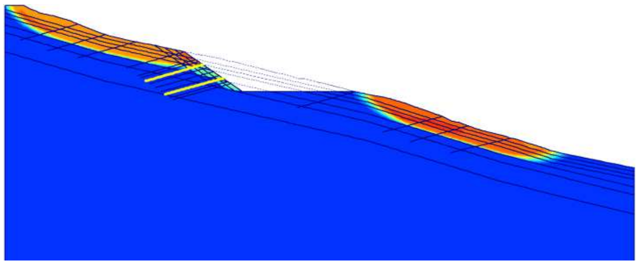

Figure 12. *Model 2, Static, 10.3 m Excavation, w=18%.*

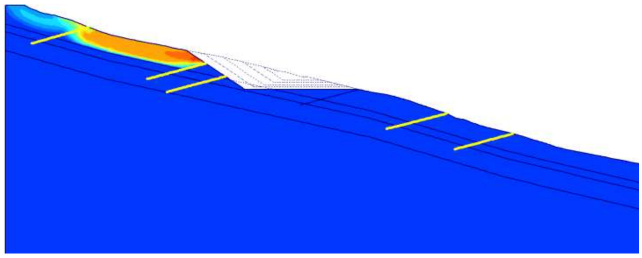

Figure 13. *Model 2, Seismic, 10.3 m Excavation, w=18%.*

5.1.2. Piles

The reinforced concrete piles used in this study are spaced of 1.8 m with a diameter of 60 cm and a length of 15 m, a normal stiffness EA=3.14×10^{6} kN/m and a flexural rigidity EI=7.07×10^{4} kN.m^{2}/m. Figures 14 and 17 summarize the needed number of pile rows to maintain the slope stable for both models. The number of pile rows increases with the increase of both excavation's depth and water content. Figures 15, 16, 18 and 19 illustrate the location of applied piles on both models.

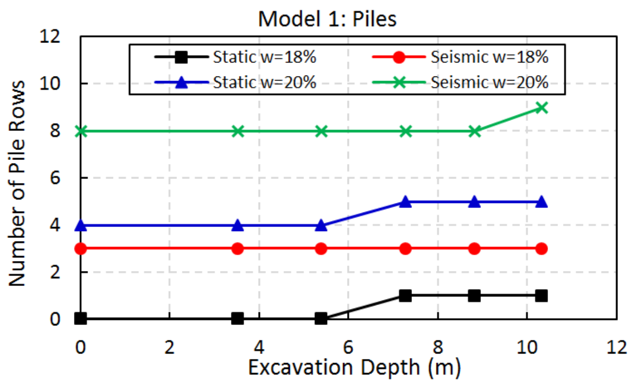

Figure 14. *Model 1, Variation of Number of Pile Rows with the Variation of Excavation's Depth and Water Content.*

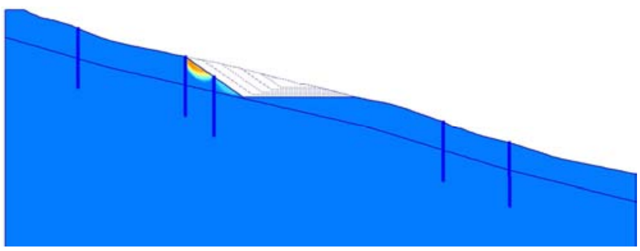

Figure 15. *Model 1, Static, 10.3 m Excavation, w=20%.*

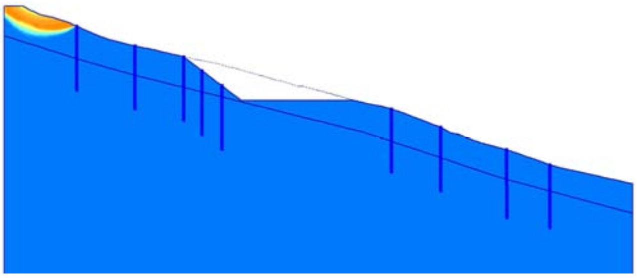

Figure 16. *Model 1, Seismic, 10.3 m Excavation, w=20%.*

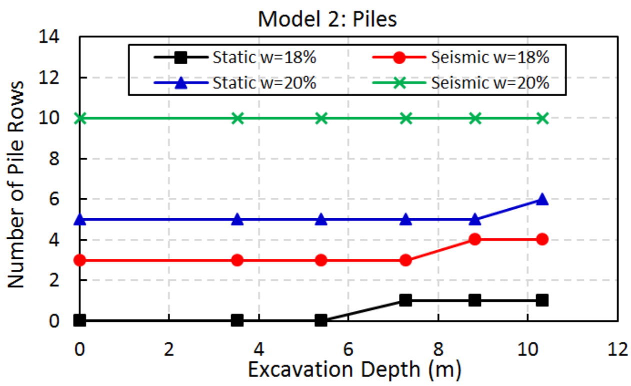

Figure 17. *Model 2, Variation of Number of Pile Rows with the Variation of Excavation's Depth and Water Content.*

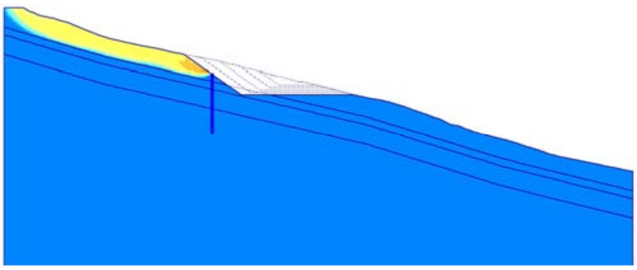

Figure 18. *Model 2, Static, 10.3 m Excavation, w=18%.*

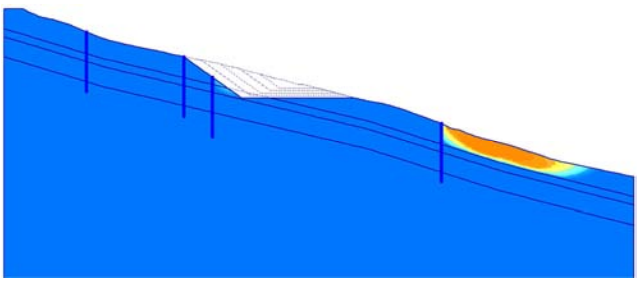

Figure 19. *Model 2, Seismic, 10.3 m Excavation, w=18%.*

5.2. Vegetation

Slope stabilization using vegetation has found wide applications since it was developed in the late of 1970's [21, 31]. Vegetation helps stabilize slopes in many ways including high biodiversity, low maintenance, self-sustainability and being environmentally-friendly [32]. Vegetation influences slope stability through hydrological and mechanical effects.

Hydrological effects involve the removal of soil water by evapotranspiration through vegetation thus reducing the soil weight, which can lead to an increase in soil suction or reduction in pore water pressure, hence an increase in the shear strength [24]. The depth of rooting affects soil moisture depletion; deep-rooted species can sustain maximum transpiration rates for greater durations, thus drying the soil at greater depths compared to shallow-rooted vegetation [33].

The shear strength of the soil is also increased through the mechanical effects of the plant root matrix system. The density of the roots within the soil mass and the root tensile strength contribute to the ability of the soils to resist shear stress. Deep tree roots penetrate into the compacted layer and tie the layers together, preventing slides [34]. In addition, roots are self-repairing, regenerating and adaptive [24].

The effects of vegetation have been incorporated in slope stability analysis by using conventional limit equilibrium method [35]. In limit equilibrium methods, the shear strength of the soil along a potential slip surface is assumed to be fully mobilized at the point of failure. The Mohr-Coulomb equation describing the shear strength:

$$\tau = c' + (\sigma - u) \tan \varphi' \tag{1}$$

By incorporating the effect of root reinforcement, the equation becomes:

$$\tau = (c' + cR) + (\sigma - u) \tan \varphi' \tag{2}$$

In this study, we have taken into account both the hydrological and the mechanical effects. The hydrological effects are considered by supposing the water content in the vegetation layer remains as the initial water content (w=15%) and does not increase in the rainfall season. Also the mechanical effects are considered by taking into account the vegetation parameters cR and hR. cR is the apparent soil cohesion caused by the plant root matrix system that is added to the initial cohesion. The depth of the root zone (hR) is defined as the effective distance beyond which plant roots cause little or no effects on the soil shear strength.

The apparent root cohesion (cR) varies over the following range:

$$0 \le cR \le 20 \text{ kPa} \tag{3}$$

Three values of depth of root zone (hR) were used:

$$hR \in \{1 \text{ m}, 2 \text{ m}, 3 \text{ m}\} \tag{4}$$

5.2.1. Effect on Safety Factor

By applying the vegetation layer to both models, with increasing incremental root depth (hR) and cohesion (cR), the safety factor increased significantly as noted in tables 7 and 8.

Table 7. *Model 1, Percentage of Increase of Safety Factor with Vegetation.*

Static		Model 1 – Safety Factor			
Vegetation		w=18%		w=20%	
Depth hR (m)	Cohesion cR (kPa)	No Excavation	10.3 m	No Excavation	10.3 m
0	0	1.589	1.250	1.151	0.900
	0	1.594	1.261	1.164	0.910
1	10	1.600	1.271	1.176	0.925
	20	1.623	1.293	1.187	0.931
	0	1.607	1.352	1.193	1.021
2	10	1.616	1.413	1.201	1.052
	20	1.630	1.424	1.207	1.07
	0	1.618	1.441	1.204	1.088
3	10	1.633	1.474	1.223	1.119
	20	1.650	1.501	1.245	1.158
Increase (%)		4	20	8	29

Table 8. *Model 2, Percentage of Increase of Safety Factor with Vegetation.*

Static		Model 2 – Safety Factor			
Vegetation		w=18%		w=20%	
Depth hR (m)	Cohesion cR (kPa)	No Excavation	10.3 m	No Excavation	10.3 m
0	0	1.617	1.194	1.142	0.978
	0	1.633	1.230	1.194	1.034
1	10	1.642	1.248	1.203	1.042
	20	1.657	1.257	1.212	1.047
	0	1.658	1.356	1.197	1.088
2	10	1.648	1.425	1.212	1.113
	20	1.680	1.484	1.231	1.141
	0	1.679	1.458	1.213	1.158
3	10	1.686	1.519	1.238	1.215
	20	1.692	1.516	1.262	1.240
Increase (%)		5	27	10.5	27

The above tables state the visible effect of vegetation on the slope stability in the cases of 18% and 20% water content.

5.2.2. Effect on Number of Nail Rows

The increase in vegetation's depth and cohesion leads to the decrease in the number of nail rows needed for a stable slope in both static and seismic cases. The reduction of nail rows number varies between 40 to 100%. The results of reduction percentages are summarized in table 9 and the related graphs are illustrated in figures 20 and 21 for static case.

Table 9. *Percentage of Increase of Number of Nail Rows with Vegetation.*

Nail Rows		Percentage of Reduction (%)			
		w=18%		w=20%	
		No Excavation	10.3 m	No Excavation	10.3 m
Static	Model 1	-	100%	60%	77.8%
	Model 2	-	100%	66.7%	77.8%
Seismic	Model 1	50%	40%	50%	69.2%
	Model 2	50%	40%	69.2%	78%

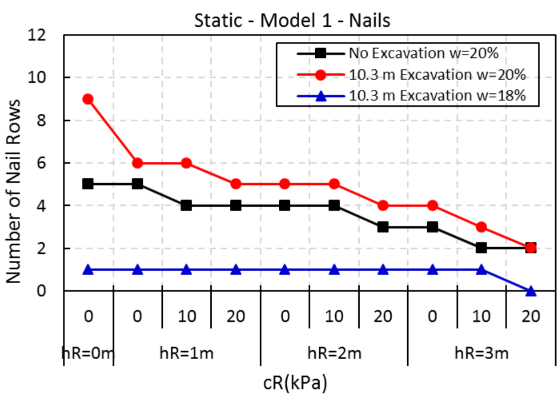

Figure 20. *Model 1, Static, Variation in Number of Nail Rows.*

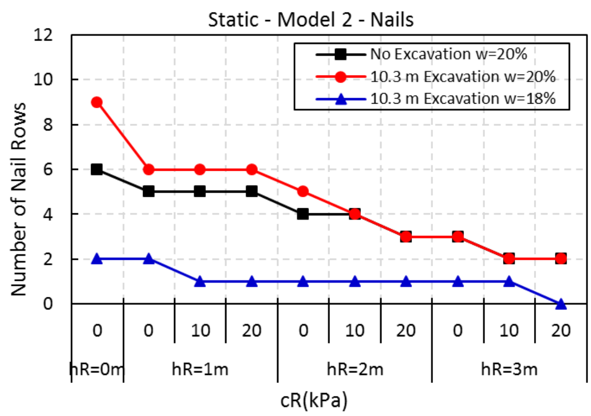

Figure 21. *Model 2, Static, Variation in Number of Nail Rows.*

5.2.3. Effect on Number of Pile Rows

The number of pile rows needed for a stable slope in both static and seismic cases decreases also dramatically by using the vegetation; this number decreases of about 50 to 70%. The results of this reduction are summarized in table 10 and illustrated in figures 22 and 23 for seismic case.

Table 10. *Percentage of Increase of Number of Pile Rows with Vegetation.*

Pile Rows		Percentage of Reduction (%)			
		w=18%		w=20%	
		No Excavation	10.3 m	No Excavation	10.3 m
Static	Model 1	-	-	50%	60%
	Model 2	-	100%	60%	66.7%
Seismic	Model 1	33%	66.7%	50%	66.7%
	Model 2	33%	50%	60%	70%

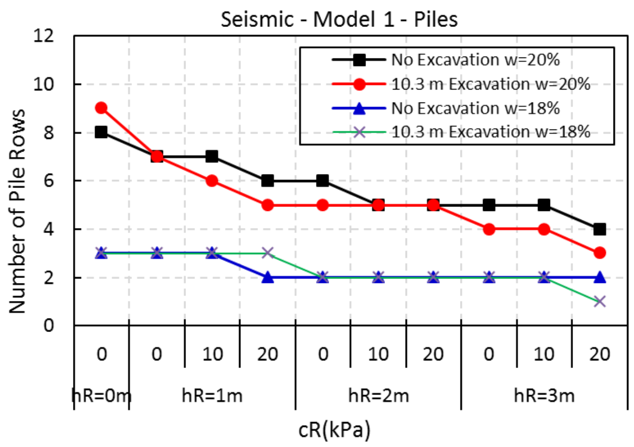

Figure 22. *Model 1, Seismic, Variation in Number of Pile Rows.*

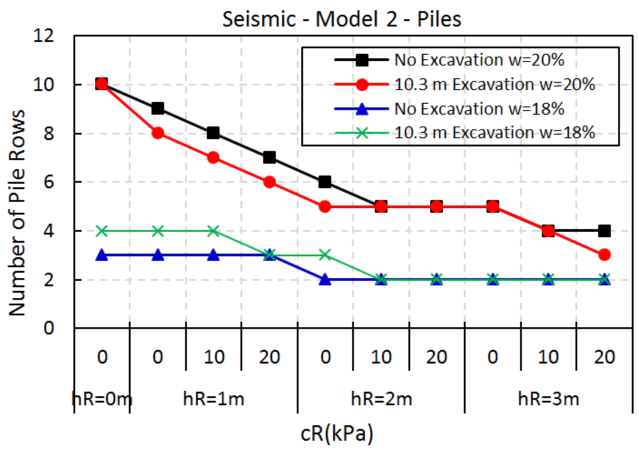

Figure 23. *Model 2, Seismic, Variation in Number of Pile Rows.*

5.3. Drainage

It is obvious that the presence of water in the slope during rainfall season contributes to slope instability. For this purpose, we studied the influence of draining trenches and sub-horizontal drains on enhancing slope stability.

First, we modeled a drainage system by a drainage trench of width of 1 m and a depth of 1, 2, 3, 4 and 5 m for both models at the top of the slope as shown in figures 24 and 25.

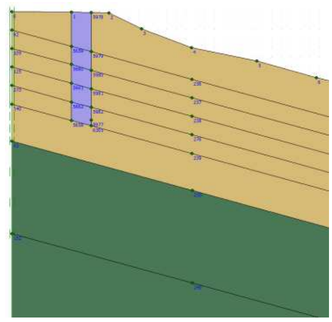

Figure 24. *Model 1, Geometry of Draining Trench.*

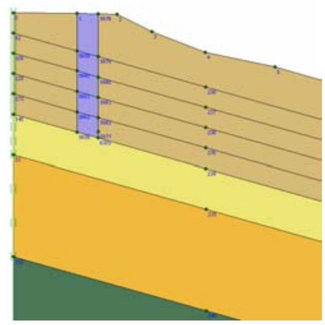

Figure 25. *Model 2, Geometry of Draining Trench.*

The trenches are constituted of filter materials allowing the water to be discharged through a longitudinally natural watercourse so they prevent the accumulation of water in the top layer. The cohesion of the filter materials c=1 kPa, angle of internal friction φ=45° and young's modulus E=80000 kPa. When applying the drainage trenches, the layer keeps its initial mechanical properties.

This partial drainage has an effect on the safety factor. It increases with the increase of the depth of the drainage trench. Tables 11 and 12 show the improvement of the safety factor with the increase of the drainage trench depth.

Table 11. *Model 1, Variation of SF with Increasing Drainage Trench Depth.*

Static	Model 1 – Safety Factor			
Drainage Trench	w=18%		w=20%	
Depth (m)	No Excavation	10.3 m	No Excavation	10.3 m
0	1.559	1.213	1.138	0.89
1	1.576	1.213	1.144	0.89
2	1.583	1.213	1.163	0.94
3	1.591	1.242	1.182	1.01
4	1.624	1.303	1.223	1.08
5	1.645	1.378	1.261	1.19
Increase (%)	5.5	13.6	10.8	33.7

Table 12. *Model 2, Variation of SF with Increasing Drainage Trench Depth.*

Static	Model 2 – Safety Factor			
Drainage Trench	w=18%		w=20%	
Depth (m)	No Excavation	10.3 m	No Excavation	10.3 m
0	1.552	1.194	1.103	0.940
1	1.600	1.194	1.135	0.940
2	1.640	1.198	1.166	0.952
3	1.680	1.238	1.188	1.026
4	1.770	1.320	1.229	1.082
5	2.293	1.440	2.293	1.440
Increase (%)	47.7	20.6	108	53.2

Since we have a noticeable increase in the safety factor, then this partial drainage definitely has an effect on the soil reinforcements, number of nail rows and pile rows. Table 13 shows the reduction percentage of number of nail and pile rows after the application of the partial drainage to obtain a stable slope. Figures 26 and 27 show the variation of number of nail rows due to partial drainage of model 1.

Table 13. *Reduction Percentage of Number of Nail and Pile Rows After Application of Partial Drainage.*

		Models	Percentage of Reduction (%)			
			w=18%		w=20%	
			No Excavation	10.3 m	No Excavation	10.3 m
Nail rows	Static	1	-	-	60%	55.5%
		2	-	50%	100%	90%
	Seismic	1	50%	60%	58.5%	61.5%
		2	100%	80%	100%	92.3%
Pile rows	Static	1	-	-	50%	40%
		2	-	50%	100%	83.3%
	Seismic	1	33.3%	33.3%	50%	55.5%
		2	100%	75%	100%	90%

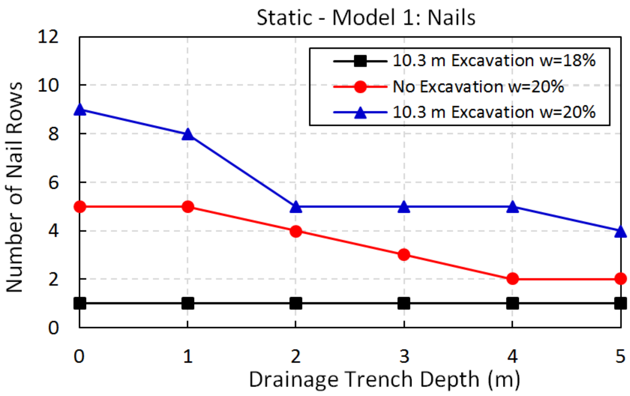

Figure 26. *Model 1, Static, Variation of Number of Nail Rows Due to Partial Drainage.*

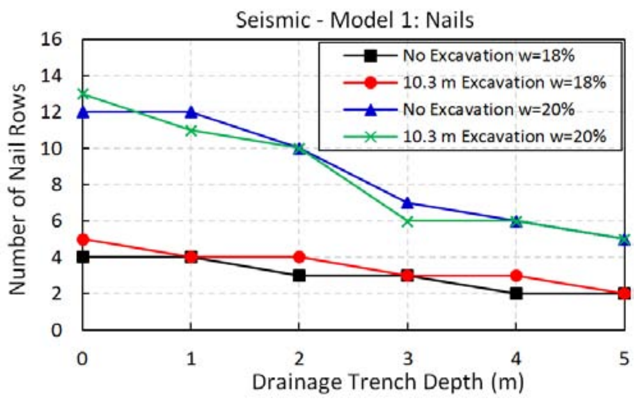

Figure 27. *Model 1, Seismic, Variation of Number of Nail Rows Due to Partial Drainage.*

Another drainage method is the sub-horizontal drains where the slope becomes completely drained. Fully drained slope takes it back to its initial condition where water content remains 15% and its mechanical properties remain the same. In this case, the slope is stable for both models in static and seismic cases even without the disposition of any kind of reinforcement, except for the 10.3 m excavation's depth in the second model where only one row of nails or piles is needed to reach stability in static and seismic cases.

6. Conclusion

In this paper, we studied the stability of a slope located in Lebanon subjected to failure during the rainfall season. The mechanical characteristics of soil were taken from boreholes results for the same site, where two models are simulated using Plaxis and Talren softwares.

Initially, the slope in both models was stable even after the application of an excavation and seismic load. The slope was studied under the effect of water where it was clear that water is a principle cause of slope instability. Water caused failure either by decreasing the shear parameters of the top layers or by the inducing pore pressure due to running water between layers.

Finding the most adequate remedy requires a perfect knowledge of the cause of the instability. First, we used soil reinforcements, nails and piles, and the results showed that the increase of the water content requires a large number of piles and nails to ensure the slope stability. The results show that piles and nails are adequate but maybe expensive remedies and they do not attack the cause of sliding but are intended to reduce or stop the deformations.

To overcome the cause of sliding which is water, vegetation and drainage were proposed and modeled. First, vegetation, which is a less expensive and an environmental friendly remedy that has hydrological and mechanical effects, was studied and modeled. As the root cohesion and depth increases, the safety factor increases and the needed number of nail and pile rows decreases dramatically. Moreover, the draining trenches and sub-horizontal drainage were tested. The draining trenches were modeled for different depths at the top of the slope, and the results showed that as the depth increases, the safety factor increases and the needed number of nail and pile rows decreases. In parallel, the application of sub-horizontal drainage has demonstrated that the slope becomes fully drained and it goes back to its initial stable state.

Acknowledgements

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