Understanding the dynamic soil properties role in a landslide

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ABSTRACT
Landslide damages have been numerous on infrastructures and on human lives, and its consequences during an earthquake might be a disaster. The purpose of this study is to evaluate how a slope will behave under seismic loading, with a special attention given to the role of dynamic soil properties in understanding slope instabilities.

RÉSUMÉ
Les effets des glissements de terrain ont été nombreux sur les infrastructures et sur les vies humaines, et les conséquences d'un séisme peuvent être désastreuses. Le but de ce travail est d'évaluer le comportement d'une pente sous l'effet d'un séisme, et une attention particulière sera donnée au rôle des propriétés dynamiques des sols dans la compréhension des instabilités des pentes.

1 INTRODUCTION

Landslide damages have been very noteworthy both on infrastructure and on human lives. Deaths due to landslides are increasing because of the rise in the world's population, particularly in landslide-prone developing countries. Some progress has been made in developing techniques to minimize the impact of landslides, although new, more efficient, quicker and cheaper methods could well emerge in the future (Popescu 2002). The Lebanese mountainous topography and its different aquifers are among the principal reasons for a landslide risk (Rahhal et al. 2003 and 2004; Rahhal and Masaad 2008). This region is much known for its tectonic activity due to the fact that it is limited in the east by the major fault of Yammouneh, extension of the Dead Sea fault that crosses the Middle East, and by many minor faults in the west. In this study, we will consider landslides that occur on the pan Arab highway, precisely in Dahr el Baidar area. In fact, this region is located between 1000 and 2000 m altitude above sea level, is subjected to a rate of rainfall ranging between 1100 and 1700 mm and has a mountainous Mediterranean climate.

The pan Arab highway is a project of road that binds all the Middle East countries together. In Lebanon, at the Dahr el Baidar area, we have noticed over the past fifteen years many landslides that cause great damage in the highway projected area, and even on surrounding roads. Hundreds of boreholes have been executed and many geotechnical studies show that rain as well as presence of poor soil are two main causes of these landslides in the area. The purpose of this research is to evaluate the importance of soil dynamics properties on a landslide and to understand how a slope will behave under seismic loading. A maximum peak horizontal acceleration a_{max} = 0.35g, will be considered as shown in the Lebanese contour map of maximum acceleration drawn by Huijer et al. 2011. Next, an overview of the project and the available geotechnical data will be presented. Afterwards, a detailed analysis of the results as well as some conclusions will be given.

2 OVERVIEW OF THE PROJECT

First, once we followed the steps mentioned by Day (2011), in the screening investigation, we continued our work by analyzing a series of boreholes made in Dahr el Baidar, in order to obtain a very clear idea concerning the nature of the soil layers. All the boreholes show that the soil beneath the highway was divided in two principal layers; a layer at the surface that was loose with weak mechanical parameters and a deeper layer of stiff soil with much higher mechanical parameters. The slip circle of all the landslides seems to be tangent to the interface of these two layers with a high contrast of parameters.

Second, based on geotechnical data, we draw a few sections of the highway. Knowing that each section refers to a different area, we chose the section that shows the biggest instability as a basis for our studies. Figure 1 shows the topographic map of a chosen area in Dahr el Baidar.

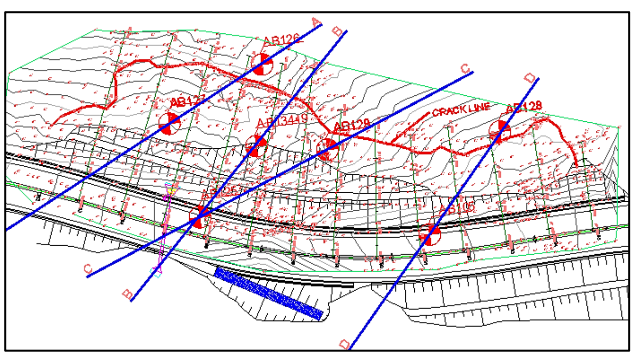

Figure 1. Topographic map showing sections and boreholes

We chose to work on the section C – C, made of four major layers, as described in table 1, and composed of: a layer of soft Marl with a very low plasticity index, a layer of Clayey Marl with a low SPT value, a layer of Marl and fractured Limestone with a higher plasticity index value and a good cohesion and a dense sand with a high SPT value becoming sandstone with depth. Values appearing in table 1 were selected and calculated based on both in situ and laboratory soil investigation data.

Table 1. Description of soil layers

Layer	Classification	c (kPa)	ϕ (°)	SPT	γ (kN/m³)	PI (%)
Marl	ML	22	23	9	1.8	10
Clayey Marl	CL	32	18	11	1.9	16
Marl and fractured Limestone	CL – ML	28	24	25	1.9	14
Sand, silt, Sandstone	SM	10	40	45	2.0	–

The section C – C is represented in figure 2 below. In order to understand the behavior of the soil during an earthquake, and to analyze the spectral response at the surface, we chose three specific points at the surface as shown on figure 2. The first point (1) is not influenced by the clayey marl layer, the second point (2) is above all the layers, and the third point (3) isn't influenced by the marl layer on the surface. The location of each point is very important to determine which soil is influencing the most the seismic response of the slope.

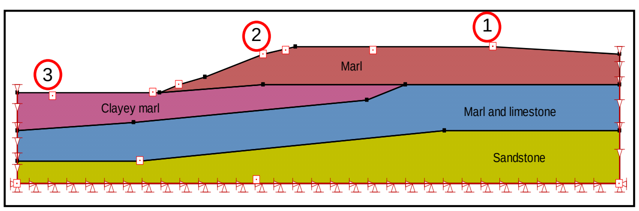

Figure 2. Section C – C with the location of the three points at the surface

3 EVALUATING THE EFFECT OF THE DYNAMIC SOIL PARAMETERS

In this section, we will emphasize on the dynamic parameters G_{max}, G/G_{max} and damping ratio of the soil, and determine their effects on the surface of the section C – C. In the calculations, the accelerogram produced by the El Centro earthquake will be considered; it happened in 1940 in California with a 6.6 magnitude, and lasted 10 s.

3.1 Effect of G_{max}

The low strain shear modulus G_{max} is a function that varies with the soil type of each layer. Before proceeding with our simulation, we have to calculate the value of G_{max} for each layer of the section C – C.

In order to calculate G_{max}, two different equations depending on the soil type are used: equation [1] (Seed and Idriss, 1970) will be used for granular of soil layer, whereas equation [2] (Mayne and Rix, 1993) will be considered for cohesive soil.

$$G_{max} = 1000K_{2,max} \times \sqrt{\sigma'_m} \quad \text{with} \quad \sigma'_m = \sigma'_v \times \frac{1+2K_0}{3} \qquad [1]$$

Making an assumption that the soil is isotropic, we will use the values established by Seed and Idriss (1970) for $K_{2,max}$. As the layer of Sand, Silt and Sandstone, is considered to be a very dense sand, the magnitude of $K_{2,max}$ will be taken equal to 75.

Based on the work of Mayne and Rix (1993), the G_{max} of cohesive soils can be estimated as in equation [2].

$$G_{max} = 625\left(\frac{1}{0.3+0.7e^2}\right) \times OCR^k\sqrt{P_a\sigma'_m} \quad \text{with } k = \frac{PI^{0.72}}{50} \qquad [2]$$

Therefore, in order to calculate the values of G_{max}, we need to determine the maximal depth of each layer, the OCR value, the plasticity index and the $K_{2,max}$ value.

All input data is shown in table 2 below, as K_0 is taken equal to 1 for an isotropic soil.

Table 2. Description of soil layers

	Max depth	$K_{2,max}$	OCR	PI	σ'_m
Marl	9.5 m	–	1	10	73 kPa
Clayey Marl	13.5 m	–	1	16	107 kPa
Marl and Limestone	21 m	–	1	14	172 kPa
Sandstone	34 m	75	–	–	297 kPa

After calculation, we obtain the values of G_{max} shown later in table 3.

3.1.1 Increasing the value of G_{max} for all the layers at once

To start with the sensitivity study, we have chosen to increase the values of G_{max} for all layers at once, and observe their effects on the global soil behavior. G_{max} values have been increased as shown in table 3. The initial values are those obtained earlier without any modifications, whereas the final values have been modified.

Table 3. Values of G_{max}

	Marl	Clayey marl	Marl and Limestone	Sand, Silt and Sandstone
Initial values of $G_{max,I}$ (MPa)	53	65	82	283
Final values of $G_{max,f}$ (MPa)	159	195	246	849

The spectral acceleration response in figure 3 shows a decrease of the amplification period of the soil in the three points at the surface.

$$G = \rho \times V_s^{\,2} \qquad [3]$$

$$T = \frac{4H}{V_s} \qquad [4]$$

By looking closer at equation [3], we can see that the increase of the values of G_{max}, will lead to an increase of the values of V_s. With reference to equation [4] giving the fundamental period of a soil deposit, an increase of the values of V_s will make the acceleration peaks move to smaller period values.

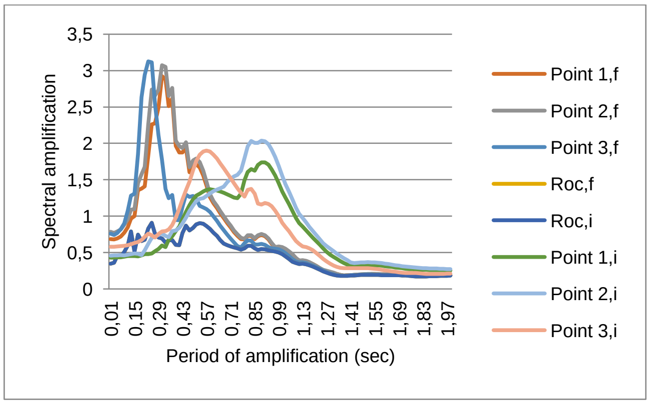

Figure3. Spectral acceleration response for each point at the surface, with initial and final values of G_{max}

We can also observe that the amplification period in the point 3 is always lower than the points 1 and 2. This is explained by the fact that an additional layer of soil is present under the points 1 and 2, which leads to a higher value of H in equation [4]. Therefore, the value of the amplification period T for the points 1 and 2 will be higher than its value for the point 3, the other parameters being left constant.

3.1.2 Increasing the value of G_{max} for each layer separately

After increasing the values of G_{max} for all the layers together, we are now interested in the effect of increasing the value for each layer of soil independently, as shown in table 4. Five scenarios may be observed (cases 0, 1, 2, 3, and 4) Therefore, we will draw the acceleration spectral response for each case and combine them in a single graphic, for each point at the surface.

The acceleration response spectra depend definitely on geotechnical conditions, as already discussed by Mohraz (1976). We can notice that the increase of the values of G_{max} in each layer separately has an interesting result. In the surface layers (case 1 and 2), the amplification depends on the nature of the layer. In fact, figure 4 shows amplification for point 1, as the figures 5 and 6 show a desamplification for the points 2 and 3

Table 4. Value of G_{max} for each scenario (case)

Case number	Marl	Clayey marl	Marl and limestone	Sandstone
0	53 MPa	65 MPa	82 MPa	283 MPa
1	106 MPa	65 MPa	82 MPa	283 MPa
2	106 MPa	130 MPa	82 MPa	283 MPa
3	106 MPa	130 MPa	164 MPa	283 MPa
4	106 MPa	130 MPa	164 MPa	566 MPa

We can conclude that the increase of G_{max} at a surface layer of granular soil will increase amplification phenomena, as its increase in a cohesive soil will reduce it. In all cases, the amplification period stays the same. As the point 1 is not located above the clayey marl layer, the curves for cases 1 and 2 do not differ from each other.

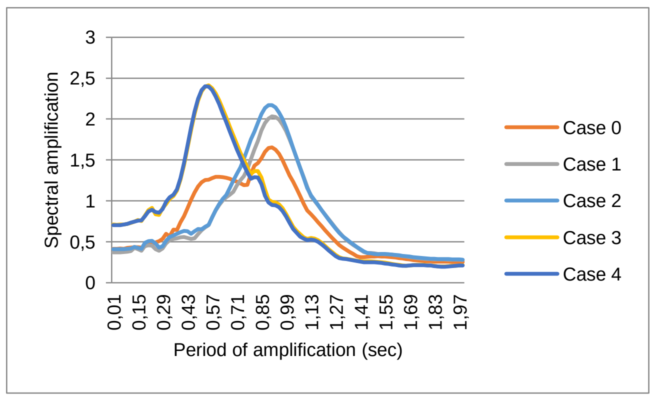

Figure 4. Spectral response for each case at point 1

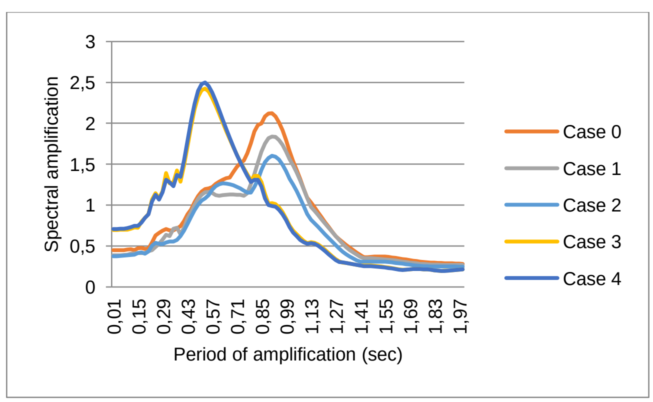

Figure 5. Spectral response for each case at point 2

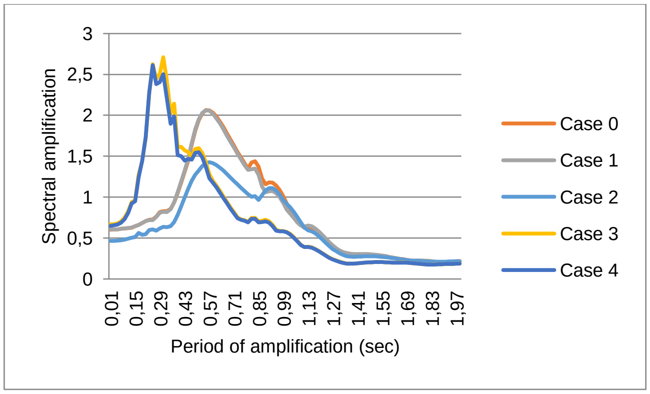

Figure 6. Spectral response for each case at point 3

The point 3 is not influenced by the marl layer; indeed its position above the clayey marl layer makes the case 0 and 1 identical. As for the layers in depth, the increase of G_{max} values will produce amplification and a decrease of the value of the period of amplification.

3.1.3 Analyzing the position of the slip circle

The study of the effect of the increase of G_{max} values with the position of the slip circle is very interesting. Figure 7 shows the different slip circle positions for each case as cited in table 5.

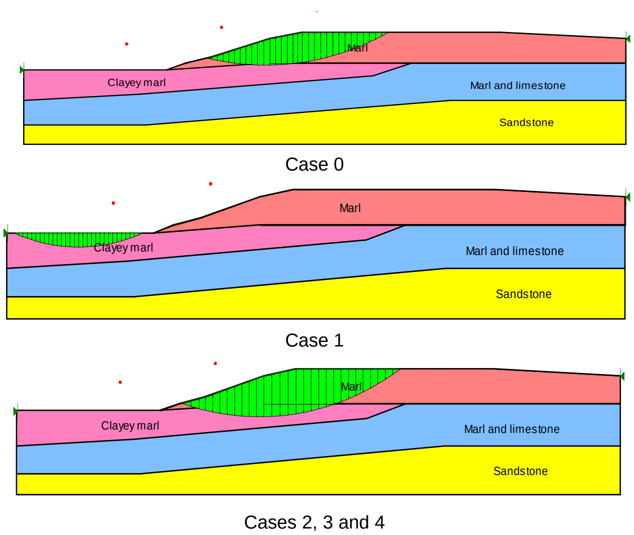

Figure 7. Slip circle for each case

Table 5. Factor of safety values for each case

Case	0	1	2	3	4
FS	1.031	1.142	1.145	0.641	0.617

For case 0, the slip circle is at the interface of the two layers of Marl and Clayey Marl. When we increase the value of G_{max} in the layer 1 (case 1), the slip circle moved to a layer with a lower G_{max}, that is the Clayey Marl layer.

In case 2, noting that both surface layers have the same G_{max}, the slip circle will include these two layers, and will not move from its position for the following cases 3 and 4.

Therefore, while increasing G_{max} in surface layers and hence decreasing the contrast of surface and deep layers, the factor of safety will increase. On the other hand, while increasing the G_{max} in the deeper layers, the contrast of deep and surface layers will increase and the factor of safety will decrease.

At this stage, we may conclude the following: the more the contrast between dynamic soil proprieties between surface and deep layers is high, the more there is a risk of landslide, and the slip circle will be located at the interface of these two highly contrasted layers.

3.2 Study of G/G_{max} curve and damping ratio

3.2.1 Sensitivity of G/G_{max} curve and damping ratio

The G/G_{max} and damping ratio curves are given by Ishibashi and Zhang (1993), as shown in equations [5] [6].

$$\frac{G}{G_{max}} = 0.5\left(1+\tanh\left(\ln\left(\frac{0.000102+n(IP)}{\gamma}\right)^{0.492}\right)\right) \times \sigma'_m{}^{0.272\left(1-\tanh\left(ln\left(\frac{0.000556}{\gamma}\right)^{0.4}\right)\right)e^{-0.0145\times IP^{1.3}}} \quad [5]$$

$$D = 0.333\frac{1+e^{-0.0145IP^{1.3}}}{2}\left(0.586\left(\frac{G}{G_{max}}\right)^2 - 1.547\frac{G}{G_{max}} + 1\right) \quad [6]$$

These equations [5] and [6] show a link between the behavior of G/G_{max} and the damping ratio. In order to draw these two curves, confining stress as well as the plasticity index must be calculated. The case 0 as shown in the table 6 represents the initial values of these two parameters. The remaining cases are the modified values used to study the effects of the G/G_{max} and damping ratio curves. Comparing the evolution of values in table 6, we notice that from one case to the one following it, values of these parameters are divided approximately by two.

Table 6. Modification of input values used to calculate G/G_{max} and damping ratio curves

Case number	Parameters	Marl	Clayey marl	Marl and limestone	Sand and Silt
0	Confining stress (kPa)	73	107	172	297
	Plasticity index	10	16	14	0
1	Confining stress (kPa)	36	54	86	149
	Plasticity index	5	8	7	0
2	Confining stress (kPa)	18	27	43	75
	Plasticity index	2	4	3	0
3	Confining stress (kPa)	9	13	21	37
	Plasticity index	1	2	1	0

When decreasing the confining stress as well as the plasticity index, the G/G_{max} curves will decrease, as shown in figure 8, whereas the damping ratio curve will increase as noticed in figure 9, as has been similarly shown by Kokusho (1980). The more G/G_{max} curve decreases, the more the damping ratio increases. The opposite behavior of these two parameters support the relation found by comparing equations [5] and [6].

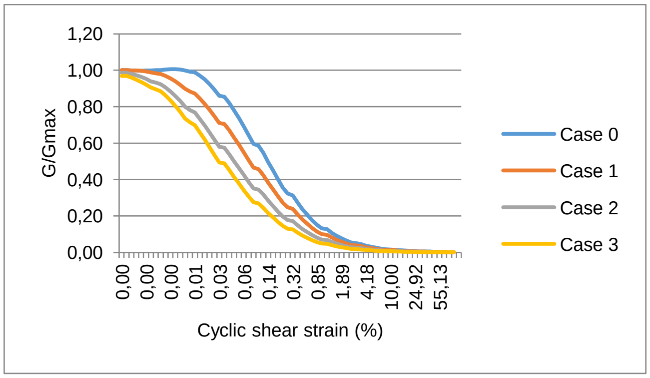

Figure 8. G/G_{max} curves for the Marl layer for each case

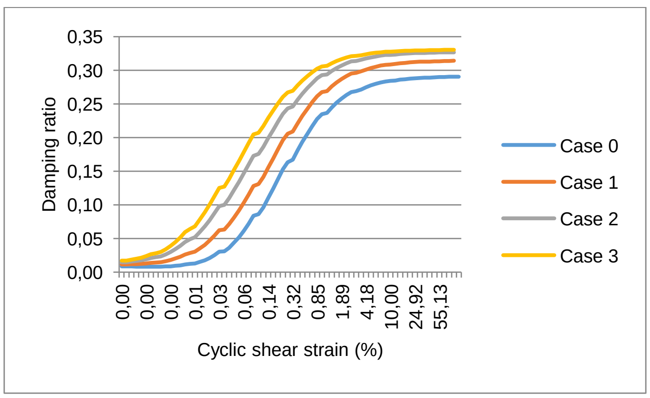

Figure 9. Damping ratio curve for the Marl layer

3.2.2 Analyzing amplification in the frequency domain

In order to analyze amplification in the frequency domain, the acceleration spectral response is drawn and the Ratio of Response Spectra (RRS) is calculated for each case and for each point at the surface. Figures 10 to 12 show the RRS for the three points at the surface.

By looking closer at the RRS curves in figures 10 to 12, we can notice that the period of amplification has increased whereas the amplification itself shows a decrease, as also shown in table 7. Indeed, the decrease of the G/G_{max} value will lead to an increase in the period of amplification values, as the increase of the damping ratio will lead to a decrease of the amplification

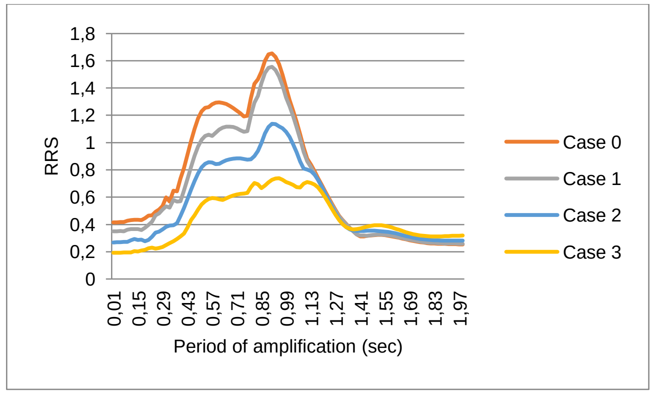

Figure 10. RRS at point 1 at the surface for each case

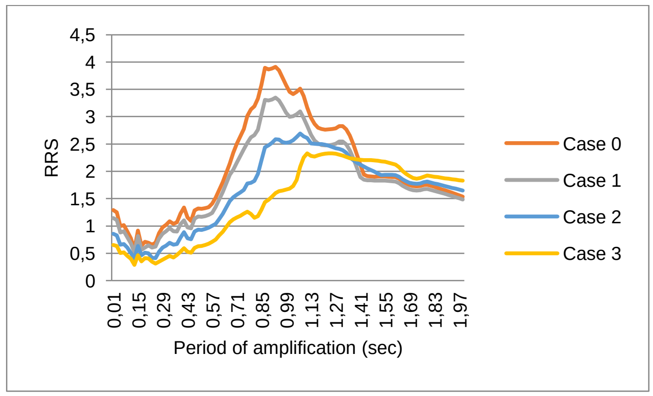

Figure 11. RRS at point 2 at the surface for each case

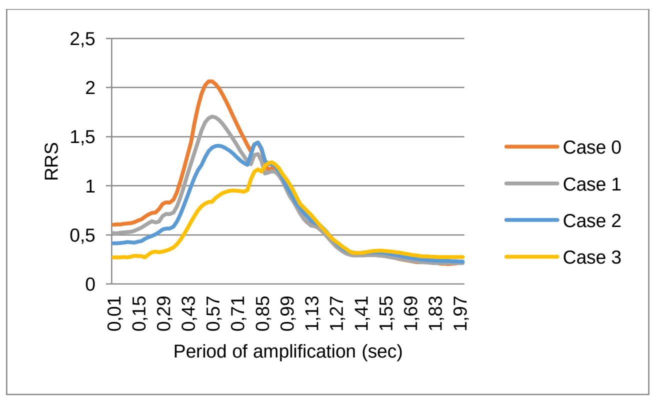

Figure 12. RRS at point 3 at the surface for each case

Table 7. Amplification and period values for each case

Case	Parameter	Point 1	Point 2	Point 3
0	Period (sec)	0.86	0.86	0.68
	Amplification	3.2	3.7	2.7
1	Period (sec)	0.91	0.91	0.69
	Amplification	2.8	3.3	2.45
2	Period (sec)	1.05	1.05	0.83
	Amplification	2.3	2.7	2.5
3	Period (sec)	1.25	1.21	0.93
	Amplification	2.1	2.3	2.3

3.2.3 Analyzing amplification in the time domain

The difference between maximum surface acceleration compared to maximum acceleration on rock, is related to the nature of soil (Kumar, 2008). Values of a_{max} at the surface after the simulation of an earthquake are gathered in table 8 below for point 1, 2 and 3.

Table 8. Amplification, period and a_{max} values for each case

Case	Parameter	Point 1	Point 2	Point 3
0	a_{max} (g)	0.43	0.43	0.59
1	a_{max} (g)	0.35	0.38	0.51
2	a_{max} (g)	0.28	0.3	0.41
3	a_{max} (g)	0.18	0.23	0.23

In initial case 0, the value of a_{max} has amplified at the surface. Indeed, a_{max} for the input was equal to 0.35g, whereas its value according to table 8 in case 0 is 0.43g for point 1 and 2. Nevertheless, amplification for a_{max} is higher at point 3 compared to points 1 and 2. Therefore, the clayey marl layer leads to a more amplified value of a_{max}.

To conclude, in the time domain, clay layers amplify the acceleration much more than granular layers, unlike in the frequency domain, where the opposite trend is observed.

3.2.4 Analyzing the position of the slip circle

For each case mentioned in table 6, the slip circle has been drawn and the factor of safety calculated as shown in Figure 13. The position of the slip circle is constant for all cases, whereas the values of the factor of safety decreases while decreasing G/G_{max} and increasing the damping ratio, as shown in table 9.

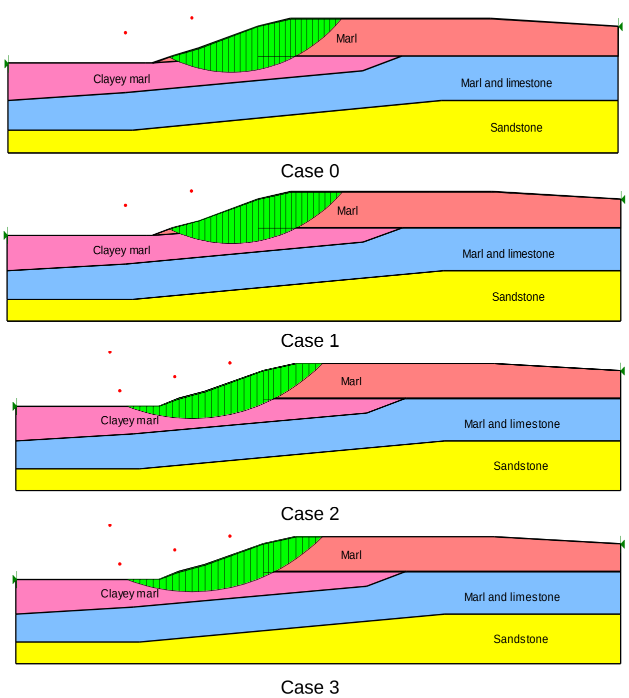

Figure 13. Position of the slip circle

Table 9. Factor of safety values for each case

Case	0	1	2	3
FS	0.644	0.711	0.938	1.012

The more we increase the damping ratio and decrease the G/G_{max} curve, the more the values of the factor of safety will increase. As we have seen earlier, the amplification is decreasing, and will lead to a higher factor of safety. Nevertheless, the position of the slip circle is still the same for all the cases, unlike in earlier cases. Indeed, by leaving the highly contrasted interface between the surface and deeper layer of soil, the slip circle will not choose a better-contrasted interface.

4 CONCLUSION

Knowledge of the soil nature is essential to determine the behavior of a soil during an earthquake. In the aim of understanding the role of dynamics soil parameters, a parametric study has been carried out. As we increase the G_{max} values of the surface layers, we noticed that the slip circle was occurring in a less stiff layer of soil and a highly contrasted interface. The increase of G_{max} values in deeper soil will not lead to the displacement of the slip surface, but will decrease the values of the factor of safety up to 55% of its initial value.

On the other hand, the decrease of G/G_{max} and increase of the damping ratio will decrease the amplification values, and lead to an rise in the factor of safety. Also, the amplification has been analyzed with respect to whether the soil was rather cohesive or granular.

The results obtained in this paper will certainly help the scientific community understand the behavior of soils in seismic situation, and will help the RUMMARE project to better interpret the causes of landslides on the Pan Arab highway at Dahr el Baidar area and give them an idea of what could happen to slopes during an earthquake. More specific results are forthcoming.

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