COMPDYN 2015
5th ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
M. Papadrakakis, V. Papadopoulos, V. Plevris (eds.)
Crete Island, Greece, 25–27 May 2015

Static and Dynamic Analyses of Dahr El Baidar Slope

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Keywords: slope stability, seismic movement, failure, geotechnical investigation, geophysical tests, correlation, soil properties, dynamic response.

Abstract. *The slope of Dahr El Baidar located on the central mountain of Lebanon hosts a section of the Arab Highway that is under construction to connect Beirut to neighboring Arab countries. This slope has experienced several failures; yet most involved geotechnical companies have investigated the slope with classical geotechnical procedures. In this paper, the analysis of the slope is performed using an integrated geo-assessment approach to identify the principal causes of failure and understand its dynamic behavior. The study includes geological, geophysical and geotechnical soil characterization of the designated area. The geological analysis reveals the presence of faults in the vicinity, in addition to a layer of weak clay at the surface. The geotechnical investigation is based on the interpretation of several boreholes. Geophysical tests are performed using ambient noise vibration technique in order to reveal the resonant frequency and thickness of the soil deposit material. A correlation between geotechnical and geophysical tests was used to establish soil properties in the studies. The above data is used towards a better understanding of the cause and occurrence of the failing zone***.** *A dynamic analysis is conducted to determine the slope amplification and compare the simulated frequencies with the measured ones.*

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1 INTRODUCTION

Estimations over the last 40 years indicate that mass movements cost each year 10-15 millions of US dollars in this small country (Lebanon) with numerous fatalities and injuries (Khawlie, 2000). Cracks in houses and roads, destruction of agricultural terraces, and scarps of different sizes are very common. Minor movements occurred in other years. Climatic and geological parameters combined with human modifications of land act simultaneously towards increasing mass movements in Lebanon.

As geological parameters have major influence in land movements, some of these large movements in Lebanon have been correlated with major earthquakes. On the other hand, climatic conditions also play an important role whereas, for example, periods of heavy precipitation in the mid to late winter season trigger landslides. Another major parameter affecting land movement is extensive man-induced activities and land alterations such as road and residential construction, deforestation, quarrying, or changing the water regime in irrigation and drainage diversion. Chaotic and rapid urban growth, which is spread throughout the country, is one of the principal causes of natural resource depletion that induces natural hazards such as desertification, mass movement, flash floods, etc. Studies dealing with mass movements (MM) in Lebanon seem to be few and mostly descriptive, yet a few cited works tackled the problem. The first to talk about landslides in Lebanon was Dubertret (1945). He included some description on landslides in the various texts “Notice de la Carte Géologique”. He delineated different types of landslides, rock falls and mudflows. Tavitian (1974) studied the Aquoura earthflow giving the engineering properties of the materials and slope stability. Khawlie and Hassanain (1984) studied the phenomenon over several areas in Lebanon giving the types and distinctive features of various occurrences. They related it to different natural and human causes, interpreting both its geological and engineering dimensions. Other studies have dealt indirectly with the subject focusing on instability of surficial materials, e.g. the engineering geological evaluation of marls (Khawlie and Ghalayini, 1985), or the analysis of the terrain and materials in assessing stability of highways (Khawlie and A’war, 1992), or the inherent lithological and geotechnical variability of the basal Cretaceous sandstone (Khawlie and Touma, 1993). The majority of previously mentioned studies treated mass movement phenomenon depending on field work purposes. Sadek, et al., (1999) has started with preliminary and simple modeling for assessing road instability in their studies related to mass movement hazards and slope stability. Rahhal et al. (2003) and Rahhal (2014) discussed the factors triggering slope instabilities in Lebanese mountains, as well as the determination of factors of safety for slopes under earthquake loading. Abdallah et al, (2005) used univariate statistical correlations to determine simple relations between classes of terrain parameters and mass movement occurrence. Youssef Abdel Massih et al. (2007), (2010) have used finite element and finite difference methods for evaluating the stability of some slopes. Several other techniques based on satellite images (Abdallah et al. 2007) were used for assessing mass movement hazard in Lebanon.

In the continuity with the geo-assessment of Dahr el Baidar slope made by Rahhal et al. (2014),, this paper presents static and dynamic stability analyses of Dahr El Baidar slope in Lebanon. The first objective of this research is to understand the causes that lead to slope failure using geotechnical and geophysical investigations. Then, 2D and 3D finite element and finite difference models are used to check the behavior of the slope under earthquake conditions.

2 SITE LOCATION

Dahr El Baidar is located at 33°48'18"N 35°45'42"E on the slope of a mountainous area in the center of Lebanon. The site is hosting a portion of the "Pan Arab Highway", a main road connecting the coastal zone to the Bekaa valley reaching east the Lebanese Syrian border. It is a vital infrastructure project that has been delayed at several instances due to slope stability problems. In-spite of the numerous geotechnical investigations, this particular site still presents a challenge to designers and contractors as a result of its complexity.

3 SOIL INVESTIGATION

3.1 Geology and tectonic of the region

The major tectonic features in Lebanon surrounding Dahr El-Baidar are (i) the Yammouneh Fault which is part of the Levantine fault extending from the Aquaba golf, passing by the Jordan valley and Dead Sea, Bekaa valley and north to the Taurus Zaghros Mountains of Turkey; (ii) the Roum Fault which is a branching of the Levantine Yammouneh fault starting from Roum village South, and extending North-West up to the capital Beirut and (iii) the Occidental flexures parallel to the Yammouneh fault regrouping a multitude of minor faults with variable activities. The Dahr el-Baydar slope is located on the center of Mount Lebanon, in a zone distanced around 5 kilometers from the Yammouneh fault, 31 km from the coastal line and 26 km from the Roum fault. The area is characterized by a significant tectonic activity. The plateau of Dahr El Baidar is a rock formation ranging from the lower to middle cretaceous (C_1 to C_3 respectively); around 6 km west of the Yammouneh fault (Dubertret, 1945). This area is positioned in a subducted zone, bounded by two minor East-West faults and highly scattered by other minor faults connected to the Yammoueh fault. The predominant ones are (i) The Kab-EliasWadi El-Delm fault, 3.5 km south in the East-West direction, limiting the Jurassic plateau of Jabal El Barouk against the depression of Dahr El Baidar, (ii) a portion of the Yammouneh fault extending around 6 km oriented NNE-SSW to the East, and (iii) a 2km stretch of Jabal El Roueiss fault in the E-W orientation. The system of faults is active however, their individual activity is difficult to trace due to the lack of instrumentation on site and close vicinity.

3.2 Geotechnical and Geophysical investigation

Aiming to study the most probable cause of the slopes failure in this region, an experimental campaign was carried out. Eight geotechnical boreholes were drilled in the area (Noted AB in Figure 1).

Table 1 shows the location (coordinates, and altitude) of the different boreholes, as well as the depth reached.

Twelve HVSR (or H/V) ambient vibration tests (Nogoshi and Igarashi (1971), Nakamura (1989)) were conducted on Dahr El Baidar site (Noted by a pin in Figure 1) using Lennartz-5s velocimeters (cut-off period of 5 seconds) connected to a CitySharkTM acquisition unit (Chatelain et al., 2000) with a 200 Hz sampling rate.

Geopsy software (http://www.geopsy.org; Wathelet et al. 2008) is used to compute the H/V spectral ratios of the registered ambient noise at several locations. A b-value of 40 was used in the smoothing procedure of Konno & Ohmachi (1998) for the computed Fourier amplitude spectra. The two horizontal components (North-South and East-West) are then combined by computing the quadratic mean and H/V ratios calculated by averaging the H/V ratios obtained on individual 10s windows. The peak observed at the H/V spectrum will be considered as the natural frequency of the soil at the location of the test.

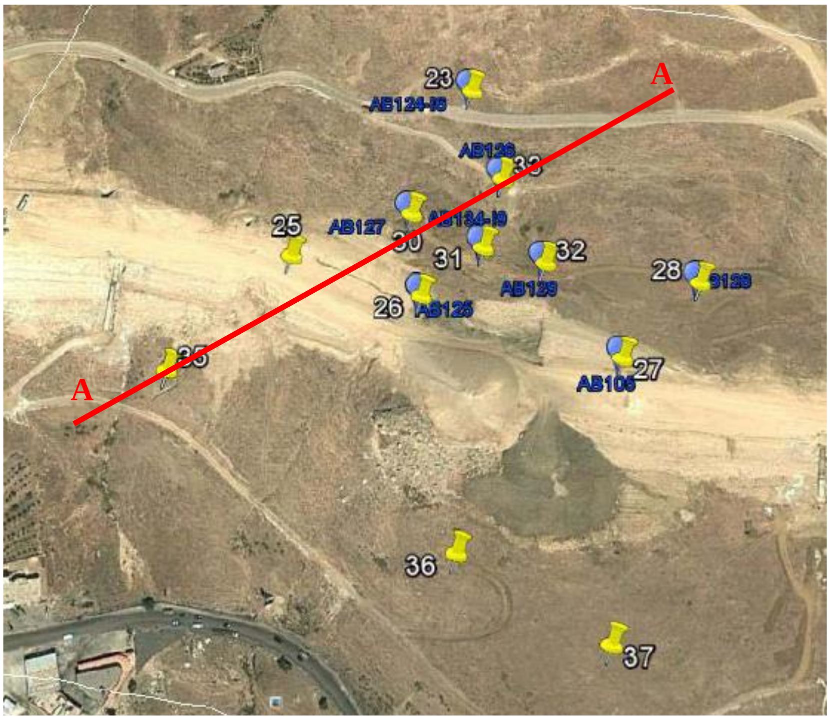

Figure 1: Site Location (from Google earth) including the location of the Pan Arab Highway, HVSR tests and Boreholes.

Table 1: Borehole Local Coordinates, Altitude, Depth reached and date realized.

Borehole	Local X	Local Y	Altitude above sea level (m)	Depth (m)
AB 105	-310399.52	-38422.13	1313.83	16
AB 125	-310528.57	-38393.22	1322.18	20
AB 126	-310482.90	-38314.05	1350.21	35
AB 127	-310539.69	-38340.86	1338.52	30
AB 128	-310352.51	-38369.13	1321.38	30
AB 129	-310452.10	-38366.86	1333.07	30
AB 134	-310491.86	-38360.21	1337.96	20

4 GEOTECHNICAL AND GEOPHYSICAL DATA ANALYSIS

4.1 Geotechnical Results

In section A-A (Figure 2), the water table is deep and the following soil layers and properties are considered: At the surface, a marly fill is found next to the crack line. Then, cemented brown sand with presence of clay of low plasticity (CL) is identified with the following shear strength properties (an effective cohesion c’ = 44kPa and an effective friction angle $\phi' = 17°$, a plasticity index of PI=18%, and a Standard Penetration Test number SPT N =11). Below, a clayey sand is found (c' = 26kPa and ϕ' = 25.8°, PI=14%, and SPT N =21). A greyish marl and limestone (with pressumeter results giving Limit Pressure P_l = 2.7 MPa and Menard elastic modulus E_m = 43.5 MPa) is interbedded between two clay layers with different properties: the upper clay has a P_l = 420 kPa, and E_m = 3.3MPa, while the lower clay has a P_l = 2.8 MPa and E_m = 163 MPa. In depth, marl with different colors (brown, grey and beige) is found with P_l = 3.9 MPa and E_m = 121 MPa. Below, Marly Sandstone is identified

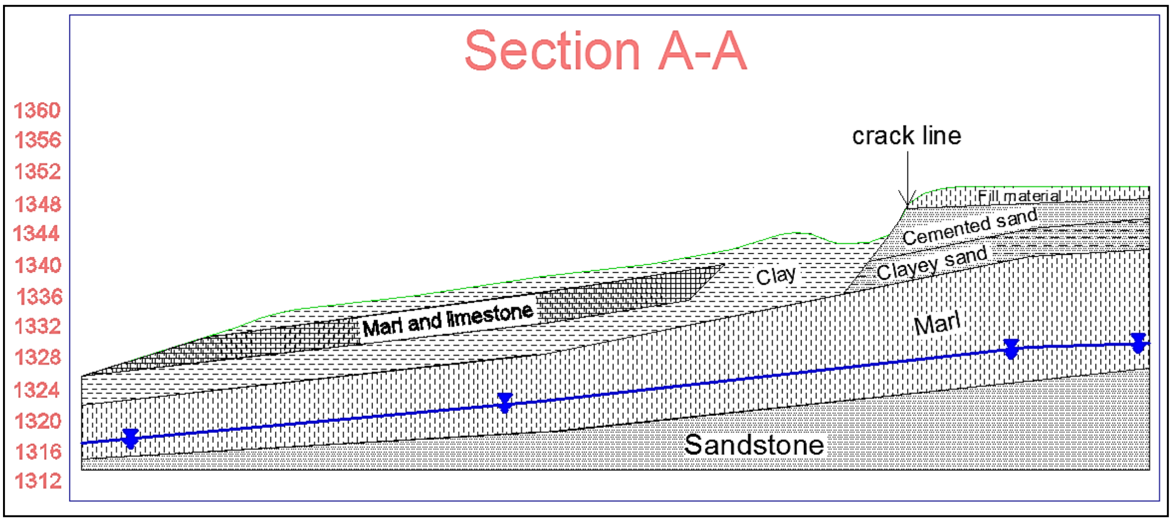

Figure 2: Soil Layers in section A – A

4.2 HVSR Geophysical Results

Due to the site heterogeneity, no clear H/V peak frequency is observed at some points. However, a dominant frequency f_0 between 3 and 5.5Hz is noticed on most of the H/V measurements. The estimated f_0 from the HVSR measurements at the borehole locations with the corresponding depth D of soft soil to the stiffer layer are reported on Table 2. Equation 1 is used:

$$f_o = \frac{V_S}{4H} \qquad \text{Eq.1}$$

Where

f_0 is the fundamental soil frequency

H is the depth of the soft layer to the bedrock

V_s is shear wave velocity of the softer layer

For values of Table 2, the shear wave velocity will range from 100m/s to 300m/s.

5 STATIC ANALYSIS ON THE SITE

A static analysis of Dahr El Baidar slope is performed using Plaxis software (Vermeer & Brinkgreve, 1998) based on the Mohr-Coulomb model material for soil behavior. Section A (Figure 2) with same coordinates presented in the geotechnical study is modeled hereafter. Soil properties shown in table 3 based on available soil data are used in the model.

Table 2: f_0 and shear wave velocity

HVSR tests	**Bore-hole**	**f_0 (Hz)**	**D (m)**	**V (m/s)**
Pt 23	AB 124	3.2	12.5	160
Pt 25		3.2		
Pt 26	AB 125	3.5	11	154
Pt 27	AB 105	5.5	4	88
Pt 28	AB 128	3.1	8	100
Pt 30	AB 127	3.8	20	304
Pt 31	AB 134	3.4	13	177
Pt 32	AB 129	No clear Peak		
Pt 33	AB 126	2.9	15	174
Pt 35		No clear Peak		
Pt 36		No clear Peak		
Pt 37		No clear Peak		

Table 3: Soil properties used in Plaxis model.

Soil Layer	Cohesion (MPa)	Friction Angle (degrees)	Dilancy Angle (degrees)	Young Modulus (MPa)	Poisson Ratio
Cemented Sand	44	17	9	23	0.2
Clayey Sand	26	25.8	13	25.6	0.2
Marl &lime-stone	28	24	12	43.5	0.2
Clay	41	12.4	7	16	0.2
Marlstone	33	24	12	62	0.2
Clayey Marl	32	18	9	10	0.2
Sandy Clay	41	12	6	25.6	0.2
Marl	24	26	13	28	0.2
Sandstone	5	30	15	24	0.3

As a result, the most probable failure surface appears at the interface Clay/Marl. The top layer of clay is sliding as shown in figure 3 below.

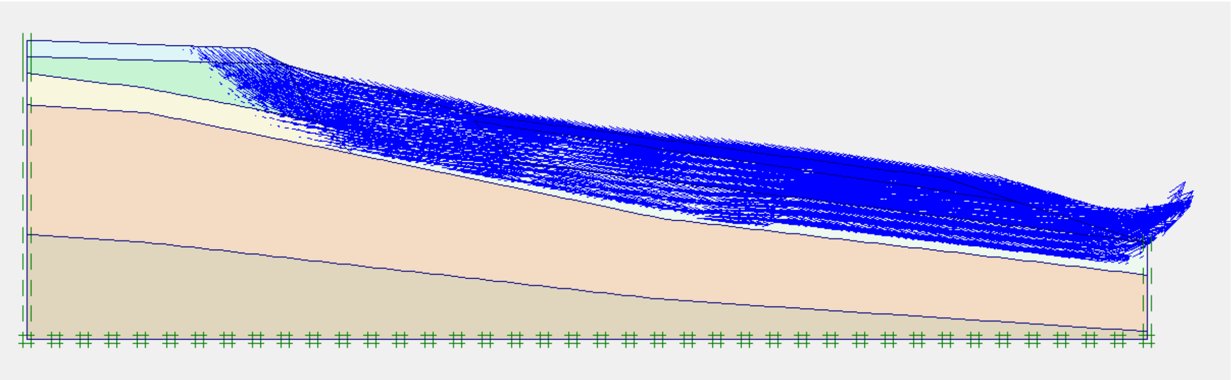

Figure 3: Failure surface of section A – at the interface Marl and clay

The initial conditions determined above reveal the state of the site at the time of soil investigation, where the slope is stable with a factor of safety of 2.9
In order to illustrate the state of the site where failure occurred, an interface is set at the top layer of Marl. This interface element will allow decreasing the mechanical properties of Marl at its interface with clay by choosing a suitable value for the strength reduction factor (R_{inter}). This factor relates the interface strength to the soil strength (c_i and φ_i , friction angle and cohesion) by:

$$c_i = R_{inter} x c_{soil} \quad \text{Eq.2}$$

$$\tan\varphi_i = R_{inter} \tan\varphi_{soil} \leq \tan\varphi_{soil} \quad \text{Eq.3}$$

where c_{soil} and φ_{soil} are respectively the cohesion and friction angle of the soil.
A total collapse of soil is seen once Marl properties decreases 1/3 as summarized in the following table:

Table 4: Mechanical properties of Marl interface.

	Initial conditions	At Total failure
Cohesion (kPa)	28	10
Friction Angle (degrees)	24	10
R_{inter}	1	0.3
F.S.	2.9	Close to 1 (i.e. Collapse)

As the soil properties at the time of slide triggering are unknown and after obtaining such results in the models, it is suspected that the main triggering factor is water. As we know, soils properties are affected by the presence of water especially the soils with very high fine contents (marl and clay). These soils lose an important part of their cohesion in the presence of water, reducing at the same time their shear strength.

Knowing that a 2D model do not represent accurately the failure shape and the complete behavior and heterogeneity of the site, a 3D model was conducted using FLAC^{3D} software. The soil is assumed to be composed by 3 layers: Clay, Marl and Sandstone in a Mohr Coulomb model with average values of soil properties obtained by geotechnical tests as shows the following figure.

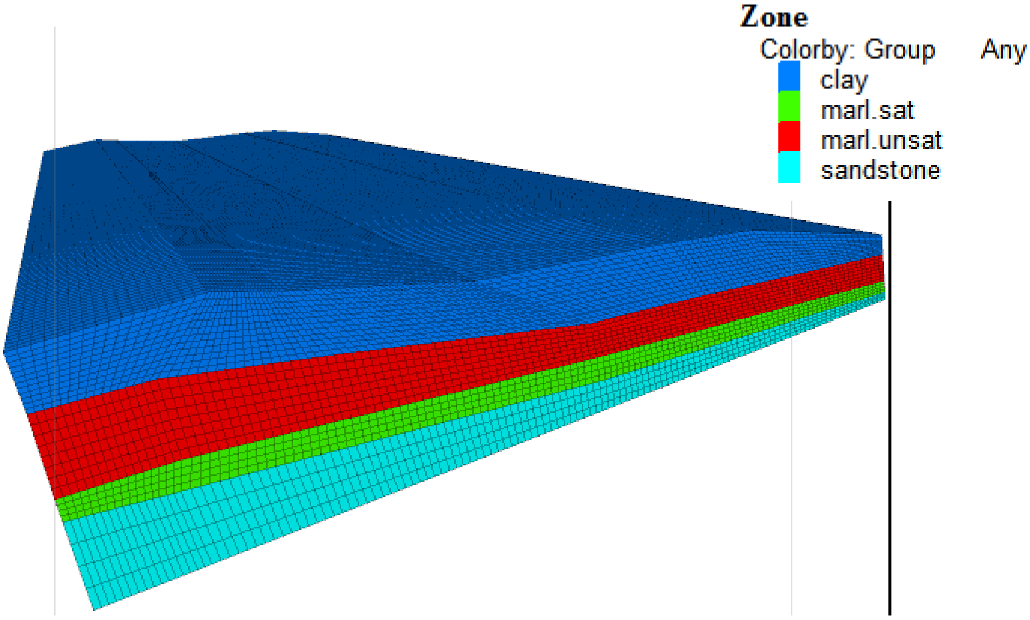

Figure 4: FLAC^{3D} static model

After using the shear strength reduction technique to determine the 3D slope safety factor, the failure surface obtained is the same as the one in the 2D section A, at the interface of Marl and Clay as shown in figure 5.

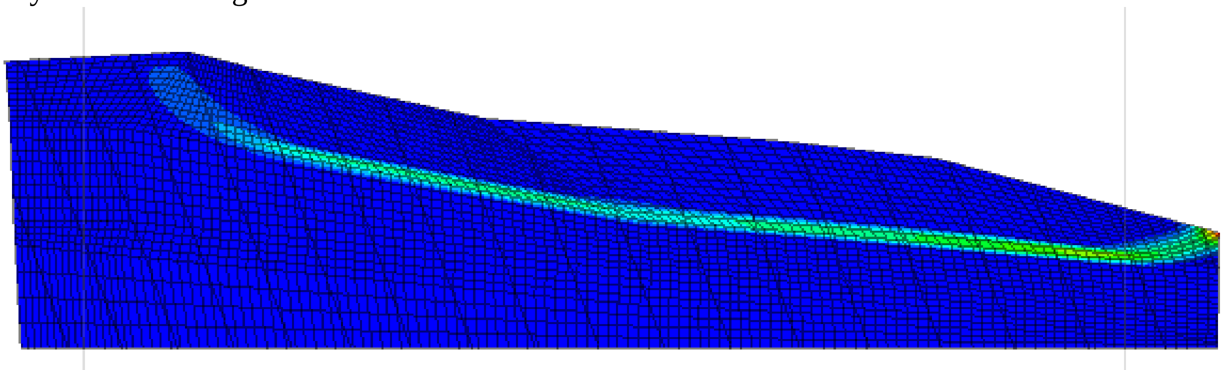

Figure 5: Section showing Failure surface of the 3D model

The safety factor of the slope in 3D model is 3.25 which is close to the one obtained by the 2D model (equal to2.9). So it can be concluded that the 3D model confirmed the results already found in the 2D model.

6 DYNAMIC ANALYSIS ON THE SITE

For the dynamic model, the same soil properties, water table level, boundary conditions and initial stresses are considered.

A mesh of 0.5m*0.5m*0.5m is used, satisfying the condition that the dimension of an element should not exceed λ/10, where λ is the minimal wavelength. $\lambda = Vs_{min}/f_{max}$ where Vs_{min}, the smallest shear wave velocity is 88m/s and f_{max} the maximum signal frequency is 20Hz.

As for dynamic boundaries, free field conditions are applied to lateral boundaries and quiet boundaries at the base in order to reduce wave reflections and model a half space at the base.
Dynamic input is applied to the model using a table signal with a time step of 0.01s and a frequency varying from 1 to 20Hz. This table is converted in stresses to apply a velocity wave in the horizontal plane according to the following equation:

$$\sigma_s = 2(\rho\ V_s)\ v_s \qquad \text{Eq.4}$$

where: σ_s= applied shear stress
ρ= mass density of the bedrock
V_s= speed of s-wave propagation of the bedrock
v_s = input shear particle velocity
and V_s is given by:

$$V_s = \sqrt{(G/\rho)} \qquad \text{Eq.5}$$

where G is the shear modulus of bedrock.
Note that the input signal is a delta like signal of flat spectrum as shown in figure 6, in order to be able to observe clearly the amplification response for all frequencies ranging between 1 and 20 Hz.

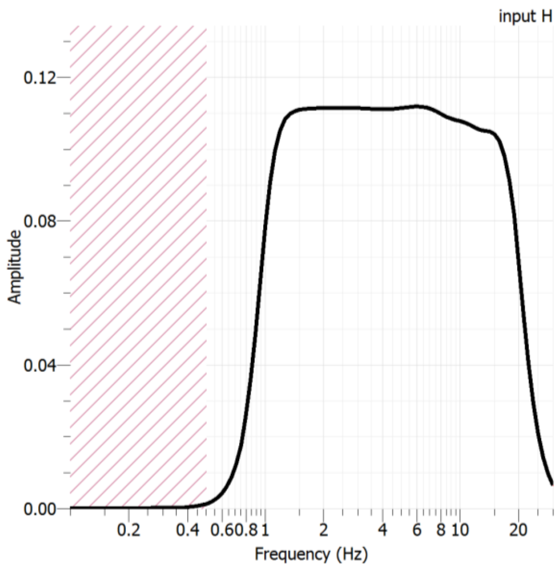

Figure 6: input spectrum

The shear wave velocity is plotted for 7 selected points. The time step of the dynamic output is 0.00172s as calculated by FLAC^{3D}. The output velocity is re-sampled in order to obtain the response with the same time step as the input signal. The figures below show the velocity spectrum of points A, B, C, D, E, F and G (cf. Figure 7) in X, Y and Z directions.

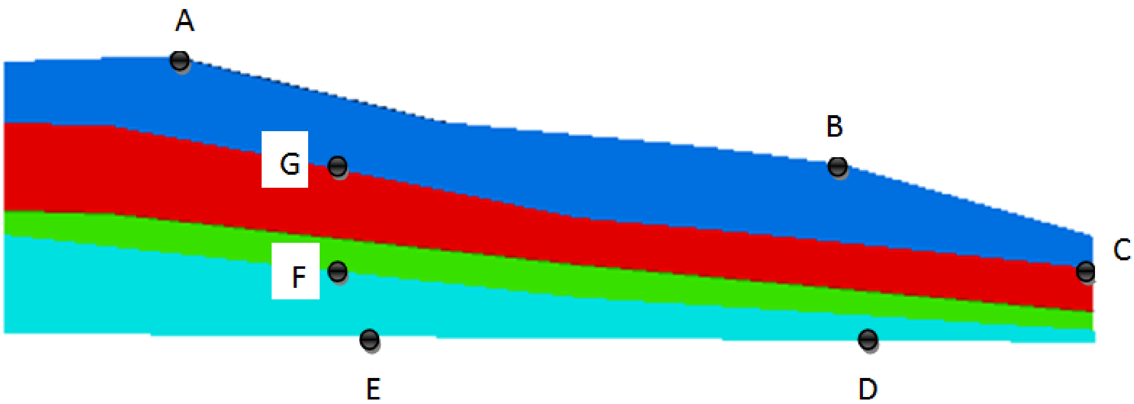

Figure 7: Selected points

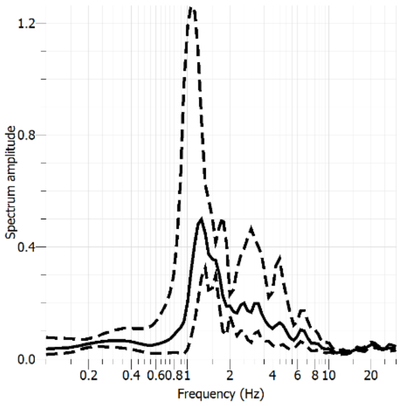

Figure 8: point A spectrum

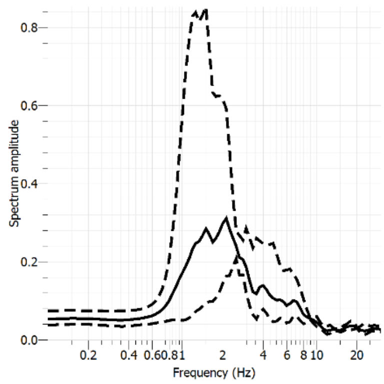

Figure 9: Point B spectrum

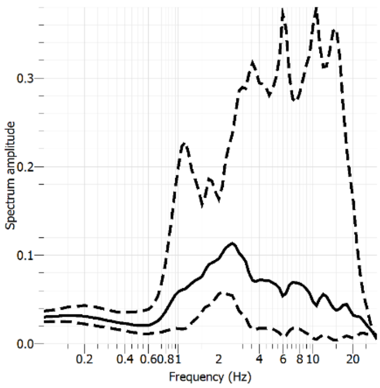

Figure 10: Point D spectrum

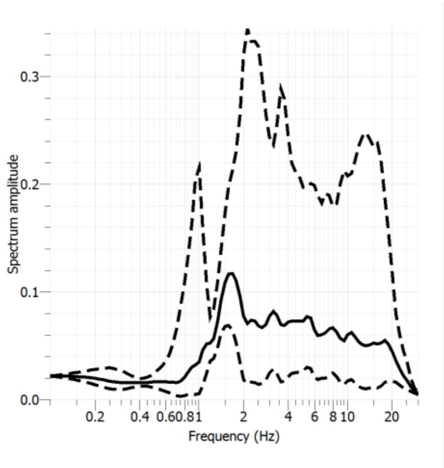

Figure 11: Point E spectrum

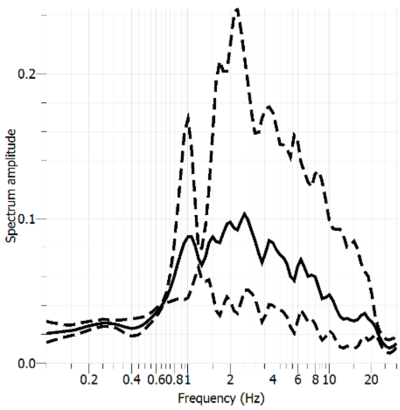

Figure 12: Point F spectrum

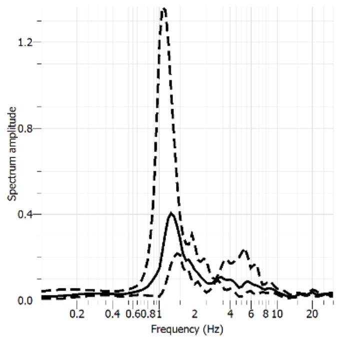

Figure 13: Point G spectrum

One can notice that at points A, B and G (Figures 8, 9 and 13), a first amplification between 1 and 2 Hz and a second amplification between 3 and 4 Hz. The first amplification may be caused by an industrial activity (confirmed by the H/V tests) and the second amplification matches well with the natural frequency found in the geophysical test. The results indicate the importance of understanding the role of soft material, especially clayey soils, in amplifying soil movements whenever this type of soils is found on top of a more rigid formation which is in our case sandstone. For points D, E and F (Figures 10, 11 and 12) at proximity of sandstone, no clear peak is observed.
After comparing the spectrums of points A and B in horizontal direction with the input signal spectrum, it is found that an important amplification is obtained between 0.1 and 8 Hz.

As a conclusion, the results of the dynamic analysis were in good agreement with the frequencies obtained by the H/V tests and have shown high amplification for a wide frequency range.

7 CONCLUSIONS

In this paper, an integrated geo-assessment is conducted on Dahr El Baidar slope – Lebanon that hosts a section of the Arab Highway under construction. The geological analysis shows the presence of faults in the vicinity as well as a layer of weak clay at the surface. The geotechnical investigation is based on the interpretation of 7 boreholes. Geophysical tests are performed using ambient noise vibration technique based on the HVSR method. The analysis of soil data based on the cross sections reveals a high fine percent, and fine soils loose an important part of their cohesion in the presence of water, due to the reduction of their shear strength. It is suspected that the failure is probably induced at the interface of two materials with different rigidities or within a soft material itself. Similarly, the dynamic analysis reveals that the natural frequency found by the geophysical tests is accurate and there is an important amplification at the surface once a dynamic wave is applied.

Further analysis is needed to evaluate the slope failure under earthquake loading and additional geophysical tests are also necessary to better estimate the dynamic properties of the soil. Scenarios of the different cross sections will be examined later to determine the static and dynamic failure surfaces and examine the triggering factors behind the slope instabilities.

ACKNOLEDGMENT

This work is part of the assessment and prediction of the behavior of various critical slopes in Lebanon carried by RUMMARE, a Research Unit on Mass Movement hazard Assessment and Risk Evaluation grouping researchers from major universities and research centers in Lebanon. The contributions of graduate students Akram Ghsossoub and Anthony Fayad should be acknowledged. The RUMMARE researchers would like to thank the Lebanese National Council for Scientific Research for funding this unit.

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