Topographic effects on the seismic responses of slopes

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15 WCEE
LISBOA 2012

SUMMARY:
This work is a parametric study of the seismic response of the ground associated with the effect of the slope. The analysis is carried out by the universal program 'FLUSH' which uses the 2D finite elements to calculate the ground column response at free field and the responses at any point of the medium. The objective of the analysis is to show the role of certain key parameters like the slope angle, the frequency content of the excitation at the base and finally, the effect of the soil column far from the slope. It was shown that the horizontal seismic movement is amplified in the crest, and undergoes an amplification-deamplification along the upper surface and the slope. This variability induces very important vertical movements on the upper surface. These effects are more significant for near field excitations than far one and for natural frequencies of ground comparable to the topographic frequencies.

Keywords: topographic effect, slope, crest, surface, amplification

1. INTRODUCTION

Observations during earthquakes showed that at a given site, the records at distinct points are different. The variations of ground motions is essentially due to traveling wave effect, attenuation effect, loss of coherency effect and local site effect (Der Kiureghian, 1996). The surface topography is one of the important influential factors of site effects. It has been recognized that the destructiveness of ground shaking during earthquakes is affected significantly by topographic amplification. The presence of a strong topographic relief (hill, ridge, canyon, or slope) has an effect on ground shaking in term of amplitude and frequency content. Also, post destructive earthquake investigations indicate that buildings located at the tops of hills, ridges and canyons, suffer more intensive damage than those located at the base. Example of these observations are cited in Boore, 1972 (San Fernando Earthquake, 1971), Celebi 1987 (Chile Earthquake, 1985), Kawase and Aki 1990 (Whittier Narrows Earthquake, 1987) and Restrepo and Cowan, 2000 (Armenia Earthquake, 1998). The recent earthquake of Boumerdes in Algeria 2003 (Laouami *et al.* 2003) brought additional evidence of severe damage of structures built on hilltops (Corso city).

One of the first studies to specifically consider the seismic response of soil slopes was conducted by Idriss and Seed, 1967 who were encouraged by the extensive landslides generated during earthquakes. They conducted a parametric study of the response of 27°clay slopes, and later of 45° slopes. They observed that the peak surface acceleration was in all cases greater at the crest of the slope than at points lower on the slopes. Vertical motions caused by the horizontal component of the base motion were generated near the crest of the slope.

Kovacs *et al* 1971 performed laboratory shaking table experiment on clay banks, they concluded that the thickness of the soil deposit was the predominant factor in determining the site response.
Sitar and Clough, 1983 used an equivalent linear, two-dimensional finite-element model to show that the motion were amplified up to 70% at the crest of the slope compared to the free field behind the

crest but they noted that these topographic effects tended to be small relatively to the amplification that occurs in the free field due to the site period.

Ashford *et al.* 2007 explored a complete range of slope angles between 30° and 90°, using the numerical model in which the geometry and geology of the configuration are simulated, developed by Deng, 1991. They analyze a stepped half space which is a simplification of the problem of a steep slope in a uniform viscoelastic material. They illustrate the significance of steep slopes on site amplification and determined the peak topographic aggravation for the free field response of a homogeneous half-space. The amplification at the crest implies that the relationship between the slope height and the shear wave velocity of the soil behind the slope is very important in quantifying the effect of topography. They also evaluate the relationship between the natural frequency of the site and topographic amplification, the results indicate two important points: the natural frequency of the site has a greater effect on surface amplification than does the topography for high levels of impedance ratio and it appears that the topographic amplification can be added onto the amplification caused by the natural frequency. The topographic effects are more significant for wavelength comparable to the irregularity geometry, and considered negligible for low frequencies (Aki, 1988, Ashford, 1997)

This modest work presents a parametric study of the slope effects on seismic ground response. The analysis is done by the FLUSH program which is based on 2D finite elements and easy to model complicated surface configurations and soil stratification. The objective of this investigation is to demonstrate the role of certain key-parameters such as slope angle, frequency content of the signal at the base and the effect of the soil column far from the slope.

2. PROBLEM DEFINITION

The model used in the analyses, shown in figure 2.1, consists in homogeneous layer overlying bedrock with shear wave velocity of 1200m/s. The soil is truncated for an artificial boundary which will transmit all the waves out of the finite model. Viscous boundaries along the plane surface were used to include the soil 3D aspects. The seismic motion is generated by SH wave type, vertically propagating.
We consider the topographic characteristic H which is the height of the slope, λ denotes the predominant wave length of the SH waves and V_s shear wave velocity. The ratio of the characteristic dimension of the slope H and the wavelength λ defines the dimensionless frequency of incident waves.
The influence of three parameters is examined in this work:

- Slope angle effect (S)
- Dimensionless frequency of incident wave H/λ
- Soil column far from the slope (Z/H)

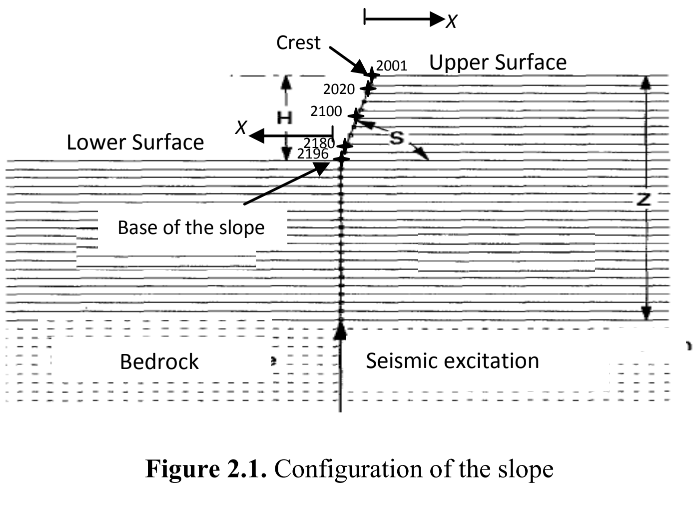

Figure 2.1. Configuration of the slope

3. EFFECTS OF SLOPE ANGLE

In order to analyze the effects of incidence angle, an isotropic, homogeneous and linear elastic soil layer with uniform properties of height $H = 20m$, shear wave velocity of 200m/s is considered. We vary the angle of the soil slope S for 20°, 30°, 45°, 60° and 75°. The results in term of acceleration are presented in figures 3.1, 3.2 and 3.3. All the responses (Horizontal and vertical accelerations) are normalized to the horizontal response at free surface (free surface of a soil column far from the slope).
At upper surface, the horizontal movement becomes complicated in the sense that it varies significantly along small distance from the crest especially in the case of stiffer slopes (75°, 60° and 45°). For instance, a maximum amplification is about 22% for a slope angle of 75°, an amplification-deamplification of the response is observed on about 20m from the crest, the tendency to stabilization towards the free surface response begins at 35m for an angle of 75° and further for lower angles. Consequently, on the entire neighboring upper horizontal surface, the differential motion appears likely to cause damage to structures.
Vertical movements are generated, their amplitude increases with the slope angle. These generated vertical movements are important up to 15m from the crest and become negligible further.
Along the slope (figure 3.2), identified by the nodes numbers (2020 to 2181), the normalized horizontal response oscillates slowly around 1 for an angle of 20°. For stiffer slopes, the response is more important at the crest and decreases while going down up to middle distance of the slope where it increase again slightly. Vertical accelerations are generated along the slope, their amplitude decreases with the slope angle. The maximum vertical acceleration occurs around the middle of the slope.
At the lower surface, it is clear that the horizontal accelerations are minimal (figure 3.3) around the toe of the slope and increase gradually with the distance away from the toe. Weak vertical accelerations appear only near the toe of the slope, 18% at the toe and only 2% two meters further.

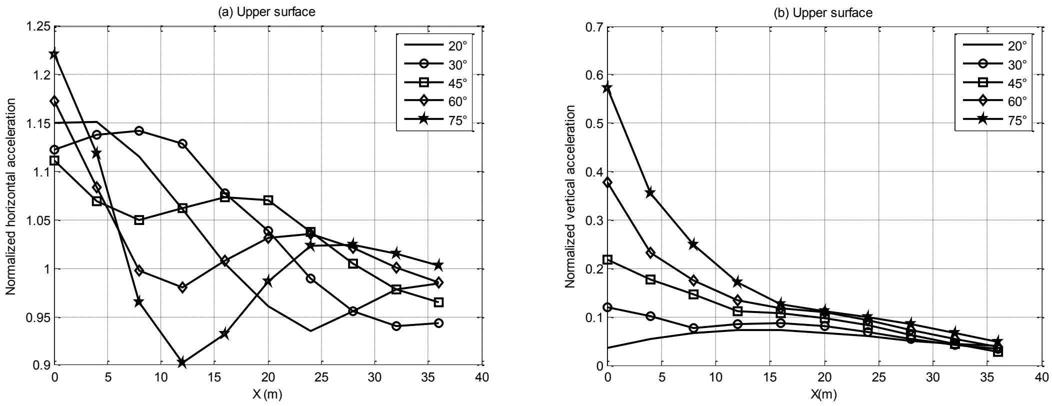

Figure 3.1. Normalized acceleration response horizontal (a) and vertical (b) on the upper surface

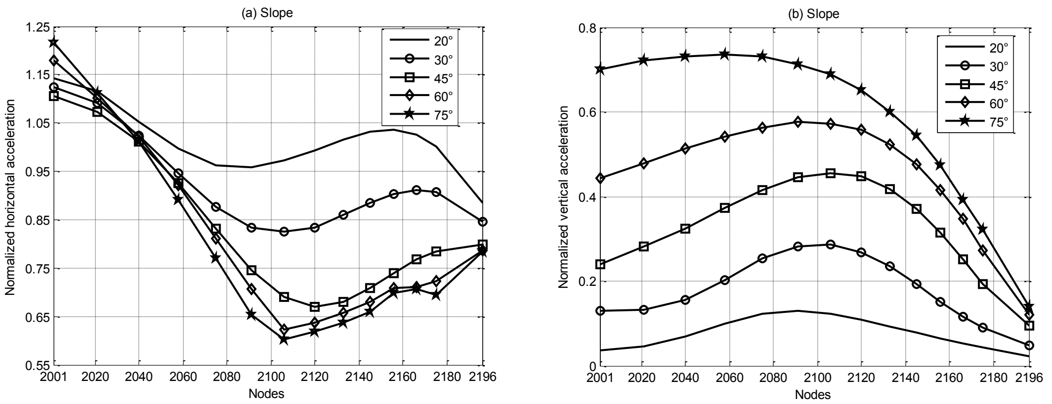

Figure 3.2. Normalized acceleration response horizontal (a) and vertical (b) on the slope

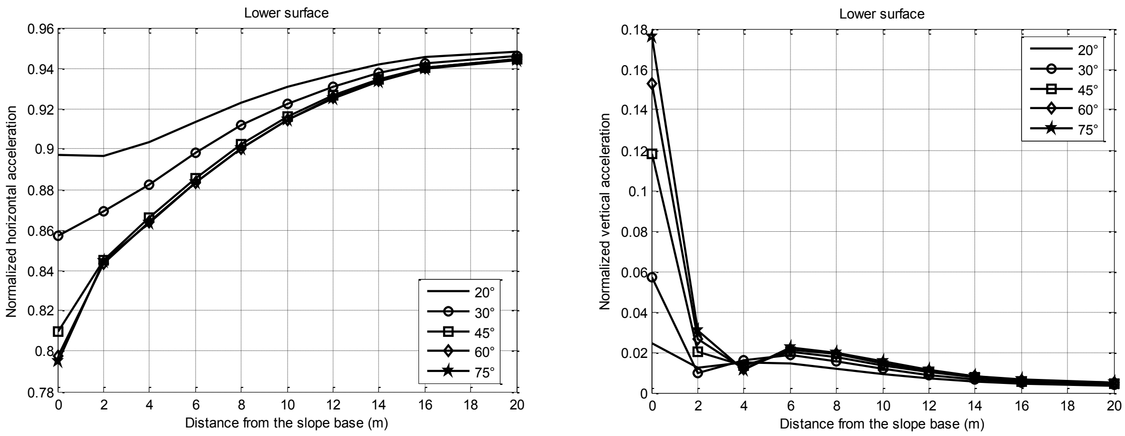

Figure 3.3. Normalized acceleration response horizontal (a) and vertical (b) on the lower surface

4. EFFECTS OF DIMENSIONLESS FREQUENCY OF INCIDENT WAVE

In this paragraph we investigate the effect of dimensionless frequency of incident wave H/λ on the seismic response (horizontal and vertical accelerations) of the upper surface. The height of the slope is fixed to $H = 16m$ with a global height of $Z = 30m$.
Results of the analyses for a 75° slope with four values of V_s (100, 200, 500, and 800m/s) are presented in figures 4.1 and 4.2. For each soil profile, two seismic excitations are considered at the bedrock:
A near field type one, recorded 20km from the epicenter with a central frequency of *7Hz* and a far field type excitation recorded 130km far from the epicenter with a central frequency of *3Hz*.
The used two accelerograms are recorded during Boumerdes Earthquake 2003 (Laouami *et al.* 2003).

From the results, it is clear that the acceleration tends to one of free field (no amplification) for shear waves velocity of 800m/s (Stiff soil) independently of the excitation (near or far field) and the vertical acceleration is minimal. We conclude that the topographic effects in case of higher shear wave velocity V_s are insignificant because of the higher value of wave length λ compared to the slope height H.

For lower values of V_s (100 and 200m/s), we observe an amplification-deamplification in the horizontal response (figure 4.1). It is very important near the crest, 28% considering near field excitation (high frequency content) and 22% considering far field excitation (low frequency). In all cases, the acceleration tends to the free field response for distances from the crest greater than 20m.

The near field excitation induces more important vertical accelerations than far field excitation (figure 4.2). These vertical accelerations attenuate quickly especially in in case of stiffer soils ($V_s > 500m/s$) to become null for distance greater than 15m.

For low values of shear velocity (soft soil), λ decreases and tends to approach the slope height H, the amplification-deamplification phenomena is observed. Nevertheless, the responses to near field excitation are not very different than those obtained from far field excitation; this is because of the seismic character in term of frequency.

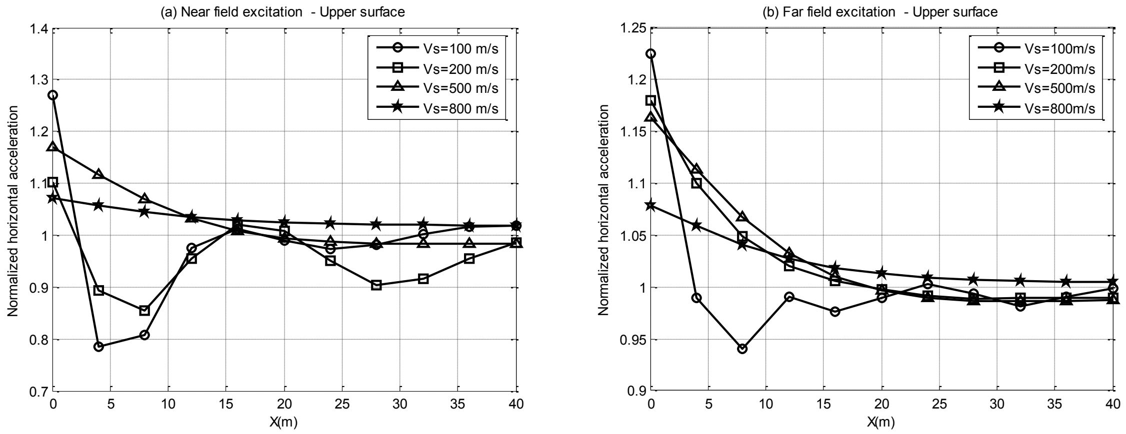

Figure 4.1. Normalized horizontal acceleration response to near field excitation (a) and far field excitation (b)

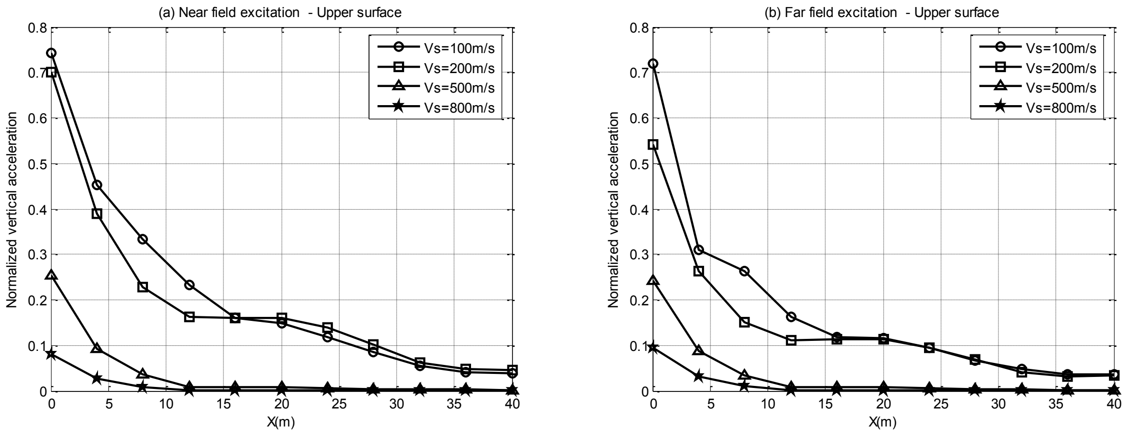

Figure 4.2. Normalized vertical acceleration response to near field excitation (a) and far field excitation (b)

5. EFFECTS OF Z/H

We investigate the effect of the ratio between the slope height H and the global height Z on the transfer functions between substratum/free surface and substratum/crest. The height of the slope H is taken equal to *16m*, $V_s = 200m/s$, $S = 75°$ and we vary the global height of Z as the ratio Z/H takes values *1, 1.3, 1.6, 2, 3, 4* and 5. Results of the analyses are presented in figures 5.1, 5.2 and 5.3. The maximum amplification ratios at free surface and crest are given in table 5.1. From the results, we use the definition of the topographic frequency f_t ($f_t = V_s/5H$) and the ground natural frequency f_n ($f_n = V_s/4Z$) given by Ashford *et al.* 1997.

Let us define T_{ns}, the free surface amplification at natural frequency f_n and T_{nc} the crest amplification at the same natural frequency. T_{ns} and T_{nc} are taken from the figure 5.1 and 5.2 for different values of the global height Z.

For low values of f_n/f_t, the slope height H is relatively short compared to the global height Z, the crest amplification T_{nc} tends to merge with that of the free surface T_{ns}. For higher values of f_n/f_t, the slope and the global heights are comparable (Z/H tends to unity), the seismic motion at the crest is more amplified. In all cases, the site amplification is much greater than the topographic amplification; this is clearly shown in figures 5.1, 5.2 and 5.3.

Table 5.1. Peak amplification ratios between bedrock/free surface T_{ns} and bedrock/crest T_{nc}

Z	f_n *(Hz)*	f_t *(Hz)*	f_n/f_t	T_{ns}	T_{nc}	T_{nc}/T_{ns}
H	3.13	2.5	1.25	12.56	14.61	1.163
1.3 H	2.40	2.5	0.96	13.08	14.89	1.138
1.6 H	1.95	2.5	0.78	12.20	13.70	1.123
2 H	1.56	2.5	0.62	14.05	15.68	1.116
3 H	1.04	2.5	0.42	18.05	19.73	1.093
4 H	0.78	2.5	0.31	11.72	12.49	1.066
5H	0.63	2.5	0.25	11.42	11.89	1.041

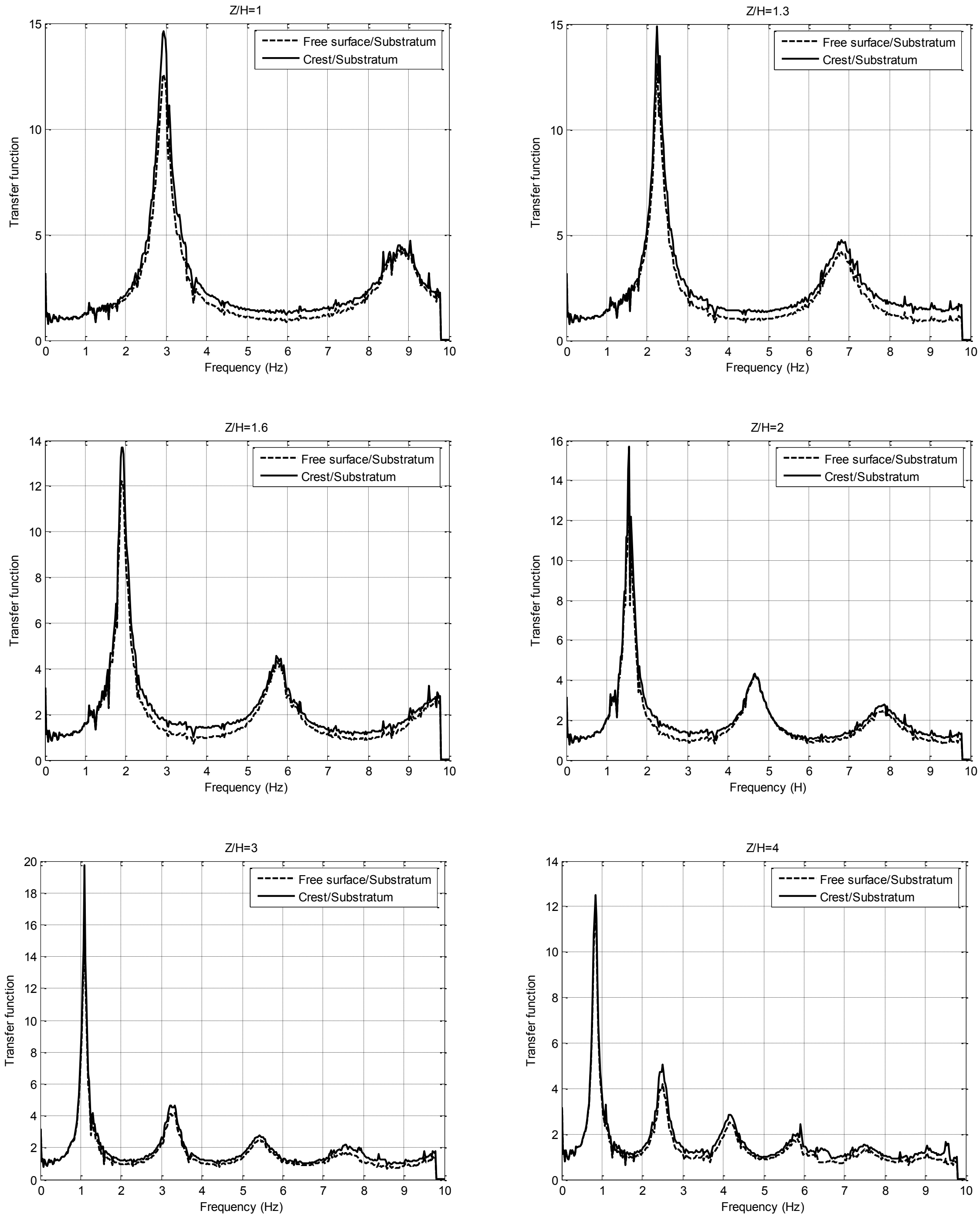

Figure 5.1. Transfer functions (free surface/Substratum, Crest/Substratum) for different ratios Z/H

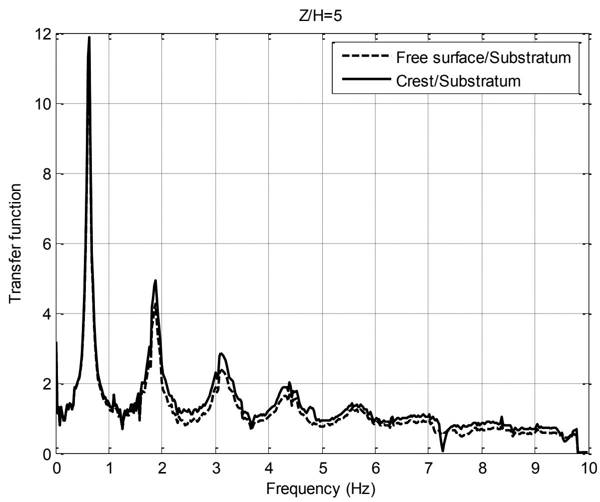

Figure 5.2. Transfer functions (free surface/Substratum, Crest/Substratum) for $\frac{Z}{H} = 5$

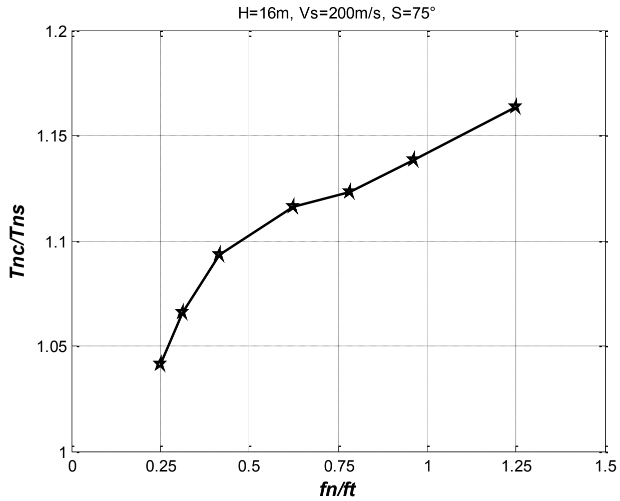

Figure 5.3. Variation of the of peak amplification ratios T_{nc}/T_{ns} with f_n/f_t

6. CONLUSION

In the present work, the seismic responses of homogeneous soil layer overlaying bedrock, presenting a geometric irregularity (slope) is analyzed along its free surface. There is no doubt that topography affects the responses at free surface by complicated cycles of amplification- deamplification. In general the responses are amplified at the upper surface of slopes and attenuated at their base. This variation induces differential movements and very important vertical components. On the basis of this modest parametric study, some general conclusions about topographic effects can be made as follows:

- The topographic effects are affected by the slope angle. Generally, the stiffer the slope is, the more the effects of topography are accentuated.
- At upper surface, the horizontal movement becomes complicated in the sense that it varies significantly along small distance from the crest especially in the case of stiffer slopes.
- An amplification-deamplification of the response is observed on short distance (comparable to the dimension of structures) from the crest, consequently, on the entire neighboring upper horizontal surface, a differential motion appears likely to cause damage to structures. This variability generates differential movements reaching 60% of the horizontal component I case of stiffer slopes.

- Along the slope the response is more important at the crest and decreases while going down up to middle distance of the slope where it increases again slightly. Vertical accelerations are generated along the slope with less amplitude than the ones on upper surface and the maximum vertical response occurs around the middle of the slope.
- The minimal responses are observed at the lower surface, especially around the toe of the slope and increase gradually with the distance away from the toe. Weak vertical accelerations appear only near the toe of the slope.
- Varying the stiffness of the soil layer, the response tends to one of free field for stiffer soils (800m/s) independently of the excitation (near or far field). For medium to soft soils, the topographic effects are significant. We conclude that the topographic effects depend on the value of wave length compared to the slope height.
- Finally, the topographic effects are influenced by the ratio between the slope and global height; this ratio can be translated to the one between the ground natural frequency and the topographic frequency. For low values of this ratio (f_n/f_t), the crest amplification is approximately equal to the free surface amplification. For comparable frequency values (f_n/f_t *tend to 1*), the seismic motion at the crest is amplified essentially for comparable heights H and Z.

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