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COUPLING BETWEEN STRATIGRAPHIC AND TOPOGRAPHIC EFFECTS ON SLOPES

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Abstract. *In this paper the seismic response of simple slope geometries under vertically propagating in-plane shear waves is assessed through two-dimensional finite element analyses to investigate the amplification of the ground motion induced by soil topography. Topographic horizontal and vertical amplification factors were evaluated through different sets of analyses of slopes overlying a compliant bedrock. The effect of soil non-linear behavior was accounted for through equivalent-linear approximation, varying the range of shear strains in which soil responds linearly; to this purposes several relationships describing the variation of normalized shear modulus and damping ratio with induced shear strain were adopted. Finally, the influence of the amplitude and of the frequency of the input motion was also analyzed.*

The results of the analyses confirmed that a complex interaction exists between stratigraphic and topographic effects and that the two effects can be neither evaluated independently nor easily uncoupled.

Specifically, horizontal and vertical topographic amplification factors were found to depend on the tendency of soil to exhibit a non-linear behavior and on the degree of non-linearity arising in its seismic response. These, on turn, are related to all the factors affecting non-linear dynamic response: soil stiffness and damping ratio at small strain, characteristics of the input motion and non-linear stress-strain relationship. Finally, the comparison with the results of linear visco-elastic analysis showed that without accounting for soil non-linear behavior, topographic amplification factors may result underestimated.

1 INTRODUCTION

Studies on seismic response of slopes, generally, deal with case-studies (e.g. [1-6]) or are systematic parametric studies carried out to evaluate inertial and/or weakening effects (e.g. 7-10) or to assess topographic amplification [11-16]. In the latter cases seismic response analyses were carried out and soil behavior was assumed either linear visco-elastic (*LVE*) [11, 13-15] or non-linear through the equivalent-linear (*EL*) approximation [1, 2, 12]. Generally, the case of incoming in-plane shear waves (SV waves) was considered.

In this framework the numerical evaluation of topographic effects is usually performed decoupling the topographic effects and the effects due to heterogeneities in soil profile (hereafter referred to as stratigraphic effects) from the computed site response. To this purpose the results of *2D* seismic response analyses, accounting for both stratigraphic and topographic amplification, are generally compared with *1D* analysis results reflecting only stratigraphic effects.

Some studies investigated topographic effects by considering the case of a slope in a homogeneous half-space [15, 17, 18], other studies included the stratigraphic amplification by introducing a rigid [1, 12-14] or a compliant bedrock [2, 19].

Generally, few are the systematic parametric analyses which account for both non-linear soil behaviour and for the presence of a compliant bedrock.

The present paper describes the results of *2D* seismic response analyses of slopes subjected to vertically propagating *SV* waves using the finite element (*FE*) code *QUAKE*/*W* [20]. The analyses were carried out: *a*) varying the slope angle, the frequency and the amplitude of the input motion; *b*) considering the case of slopes over a compliant bedrock; *c*) assuming. that soil behaves as an equivalent-linear (*EL*) visco-elastic material. Table 1 provides an overview of the cases and parameters considered in the analyses.

***2D* ANALYSIS (H = 50 m, D = 250 m, L/H = 30)**

Effect	Model	Soil properties	Bedrock properties	i (°)	a_o (g)	f (Hz)	Figure
Coupling, Plasticity index *PI*	Homogeneous soil layer (*PI* = 30, 50, 100, 200 %) over compliant bedrock (I_R = 0.2)	γ = 20 kN/m^3 ν = 1/3 V_s = 500 m/s	γ_b = 20 kN/m^3 ν_b = 1/3 $V_{s,b}$ = 2500 m/s	30 45 60	0.1	2 , 3, 4.5	2
Soil non-linear behavior	Homogeneous soil layer (*PI* = 30 %) over compliant bedrock (I_R = 0.2)	γ = 20 kN/m^3 ν = 1/3 V_s = 500 m/s	γ_b = 20 kN/m^3 ν_b = 1/3 $V_{s,b}$ = 2500 m/s	45	0.1 0.2 0.3	3	3
	Homogeneous soil layer (*PI* = 30, 50, 100 %) over compliant bedrock (I_R = 0.2)			45	0.1	0.5	4
	Homogeneous soil layer (*PI* = 30, 50, 100, 200 %) over compliant bedrock (I_R = 0.2)			45	0.1	0.5, 2	5
Frequency *f*	Homogeneous soil layer (*PI* = 30 %) over compliant bedrock (I_R = 0.2)	γ = 20 kN/m^3 ν = 1/3 V_s = 500 m/s	γ_b = 20 kN/m^3 ν_b = 1/3 $V_{s,b}$ = 2500 m/s	45	0.1	0.5, 1.25, 2, 4.5,10	6

Table 1: Summary of the numerical analyses.

Figure 1 shows the scheme of the *FE* model adopted in the analyses together with the conditions imposed to the height *h* and to the width *l* of the elements of the mesh (Figure 1c) to avoid that the high frequency components of the input seismic motion are filtered out during the propagation process and to ensure the accuracy of the numerical solution.

In the analyses H = 50 m, D = 250 m and L/H = 30 (Figure 1a) were considered. A viscous Lysmer and Kuhlemeyer boundary was applied to the bottom of the mesh of the *FE* model (Figure 1b) to absorb scattered energy and mitigate the effect of wave reflections. Finally, in all the cases zero vertical displacement condition was applied along lateral vertical boundaries (Figure 1b).

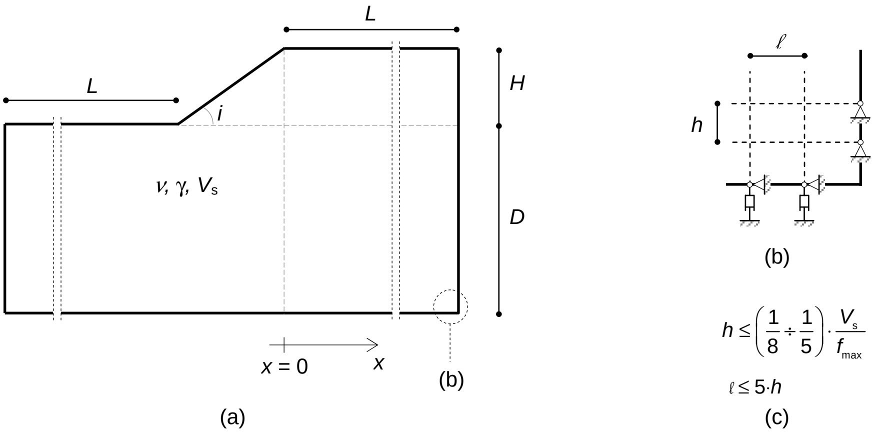

Figure 1: 2*D* FE model scheme and boundary conditions.

In all the analyses unit weight $\gamma = 20$ kN/m^3, constant shear-wave velocity $V_s = 500$ m/s and Poisson's ratio $\nu = 1/3$ were assumed for the soil. For the compliant bedrock a unit weight $\gamma_b = 20$ kN/m^3 and a value of the shear wave velocity $V_{s,b}$ = 2500 m/s were assumed; thus, the considered impedance ratio is $I_R = 0.2$. The bedrock depth was fixed at $z_b = 250$ m.

Dissipation of energy was introduced in the system through the Rayleigh damping matrix defined as a combination of the mass and stiffness matrices through the coefficients α and β which depend on the modal damping ratio. Further detail on the numerical modelling can be found in [19].

In the *EL* analyses (Table 1) the reduction of the normalised shear modulus G/G_0 and the increment of the damping ratio ξ with the strain level γ were described using the relationship proposed by Vucetic and Dobry [21] for different values of the plasticity index *PI*.

The effects of soil non-linear behaviour were investigated considering different values of the amplitude (a_0 = 0.1, 0.2 and 0.3 g) and of the frequency (f = 0.1, 1.25, 2, 3, 4.5 and 10 Hz) of the input motion and a wide range of values of plasticity index (*PI* = 30 %, 50 %, 100 % and 200 %) for which the corresponding $G/G_0 - \gamma$ and $\xi - \gamma$ curves are characterized by linear thresholds of shear strain γ_l varying from 0.001 % to 0.01 % [22].

Coupling between stratigraphic and topographic effects was examined and the obtained results are presented in terms of horizontal and vertical topographic amplification factors A_h and A_v

$$A_h = \frac{a_{h,max}}{a_{h,ff}} \qquad A_v = \frac{a_{v,max}}{a_{h,ff}} \tag{1}$$

where $a_{h,max}$ and $a_{v,max}$ are the peak horizontal (*h*) and vertical (*v*) acceleration computed at the ground surface and a_{ff} is the peak acceleration of the *free-field* (*ff*) response. The values of *a*ff were detected through supplementary *1D* analyses carried out with reference to soil columns of height *D* and *H* + *D* (Figure 1a) adopted to simulate the *1D free-field* response in front of the toe and behind the crest of the slope, respectively. Specifically, the profiles of the horizontal and vertical maximum acceleration obtained at the ground surface behind the crest and in front of the slope were normalized respect to the corresponding *free-field* values, obtaining the topographic amplification factors.

The results obtained in the analyses are discussed separately; in particular, the coupling between stratigraphic and topographic effects is discussed in section 2, the influence of non-linear behaviour is discussed in the section 3, finally, the influence of input motion frequency is discussed in the section 4.

2 COUPLING BETWEEN STRATIGRAPHIC AND TOPOGRAPHIC EFFECTS

Figure 2a-f shows the results in terms of A_h and A_v obtained for f = 2 Hz and $a_0 = 0.1g$: it can be noted that the horizontal topographic amplification factor is significantly affected by *PI* on all over the ground surface. A_h increases for decreasing *PI*, attaining its peak close to the toe of the slope. For increasing values of the slope angle the maximum values of A_h close to the toe increase, whereas maximum values close to the crest reduce. The vertical topographic amplification factor increases for increasing *PI* and reaches its maximum values, in turn increasing with the slope angle, at or close to the toe of the slope.

Also in the case f = 3 Hz and $a_0 = 0.1g$ (Figure 2g-l), horizontal and vertical topographic amplification factors are affected by *PI*: the seismic motion is slightly amplified in front of the toe and is moderately amplified behind the crest. The already observed trend of A_h is confirmed: it increases for increasing values of the angle of the slope in front of the toe and decreases for increasing *i* behind the crest.

For f = 4.5 Hz and $a_0 = 0.1g$ (Figure 2m-r) a noticeable influence of *PI* on A_h can be observed at and behind the crest of the slope where the profile of the horizontal topographic amplification factor is characterized by sharp peaks; the effect of *PI* on the vertical topographic aggravation factor is rather negligible in front of the toe of the slope while it is relevant at and behind the crest.

As expected, independently of the input frequency, the effect of soil non-linearity on the topographic amplification factors fades away as the lateral boundaries ($x = \pm$ 1500 m, not shown in Figure 2) are approached, since there the system seismic response coincides with the *1D* free field response ($A_h = 1$ and $A_v = 0$).

The influence of the non-linear behaviour of the soil on topographic amplification factors depends on the values of *free-field* accelerations of the soil deposits behind the crest and in front of the toe of the slope. For smaller values of *PI*, that is for smaller values of linear threshold shear strain γ_l, soil behaves elastically in a narrow range of shear strains and earthquake induced strains lead to a greater reduction of the shear modulus (implying a reduction of the system natural frequencies and an increase in the impedance ratio) and to larger values of the mobilized damping ratio (implying a reduction of the amplitudes of the amplification peaks).

The combination of these two counteracting effects depends on the soil stiffness at small shear strain (which influences the system natural frequencies) and on the amplitude of the induced strain levels, affected by the amplitude of the seismic acceleration arising in the system.

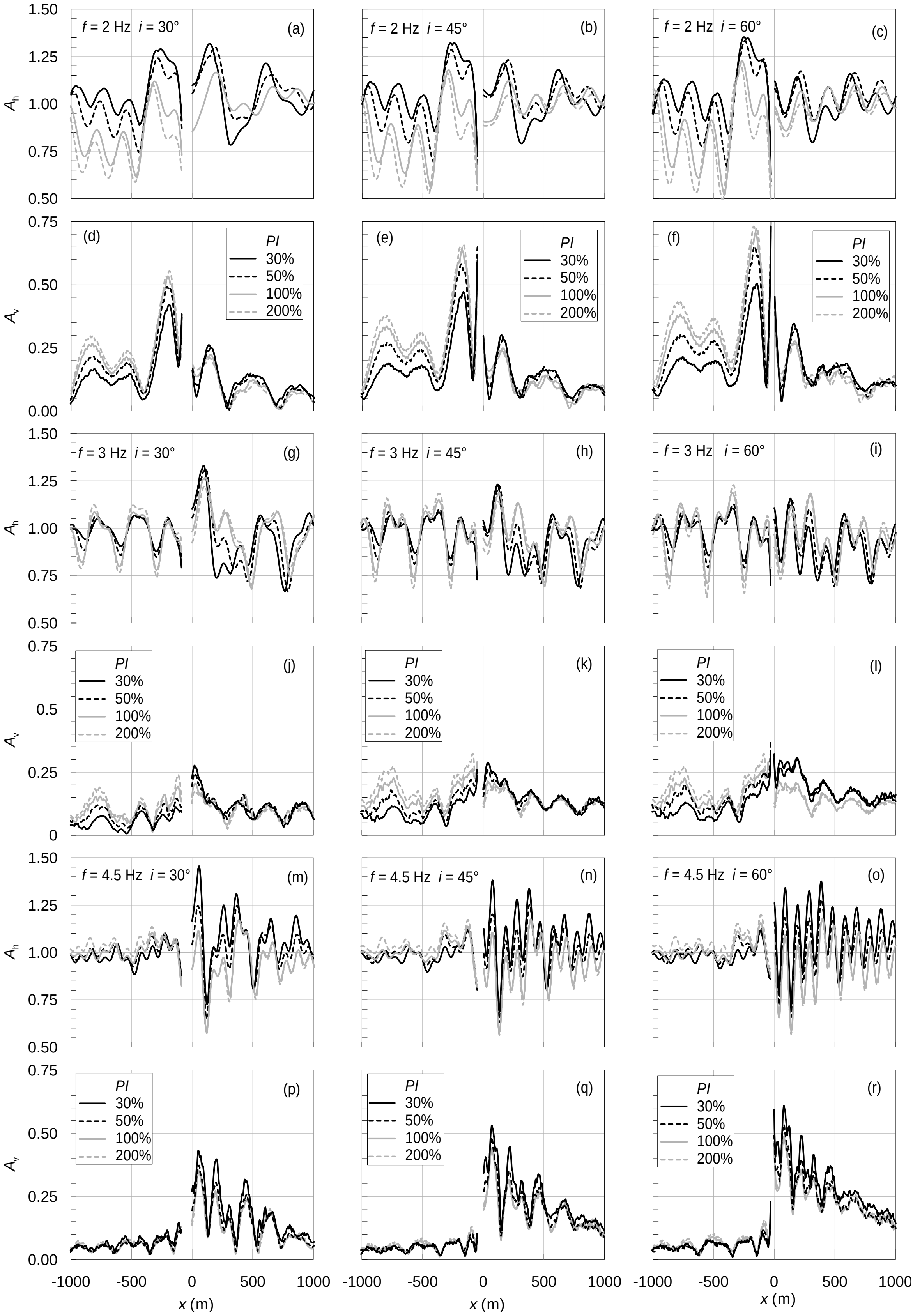

Figure 2: Horizontal and vertical topographic amplification factors computed at the ground surface for $a_0 = 0.1g$, for different values of slope angle (i = 30°, 45°, 60°), plasticity index (PI = 30, 50, 100, 200%) and input frequency (f = 2, 3, 4.5 Hz).

These results confirm that the stratigraphic and the topographic effects cannot be investigated separately since they are coupled in a complex interaction. As it could be expected for non-linear systems this interaction is governed by the system mechanical and geometrical properties and by the characteristics of the input motion.

3 INFLUENCE OF SOIL NON-LINEAR BEHAVIOUR

To point out the influence of the non-linear soil behaviour on the seismic response of the slope, different values of a_o and *PI* were considered (Table 1).

The results relevant for the case i = 45°, *PI* = 30% and f = 3 Hz are shown in Figure 3. It can be observed that the profiles of both horizontal and vertical topographic amplification factors along the ground surface are remarkably affected by the amplitude of the input motion. The influence of soil non-linear behaviour is also apparent: in fact, for increasing values of a_o, A_h is approximately increasing close to the toe of the slope, where absolute maximum amplification is attained, and is heavily decreasing close to the crest, while the profiles variously intertwine for increasing distance from the slope crest (Figure 3a). A similar trend is observed also for A_v (Figure 3b).

Figure 3 also shows the results of the *LVEB* analyses, carried out by [19] considering a slope in a homogeneous soil deposit overlying a compliant bedrock and assuming a constant value of shear modulus G and a damping ratio ξ = 5%. In this case the results are independent of the amplitude of the input motion when expressed in a normalized form through A_h and A_v. The differences in the profiles of A_h and A_v obtained in the *EL* analyses with respect to the profile evaluated in the *LVEB* analyses confirm the influence of the non-linear soil behaviour.

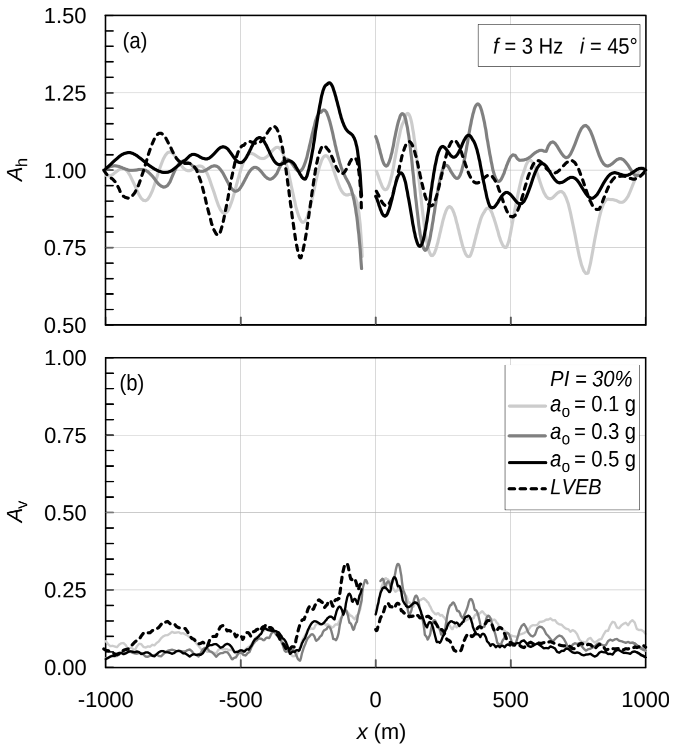

Figure 3: Horizontal (a) and vertical (b) topographic amplification factors computed at the ground surface for *PI* = 30%, i = 45°, f = 3 Hz and different input motion amplitudes a_0.

The degree of nonlinearity introduced for each analysis can be represented through the profiles of the mobilized values of the normalized shear modulus G/Go and damping ratio ξ.

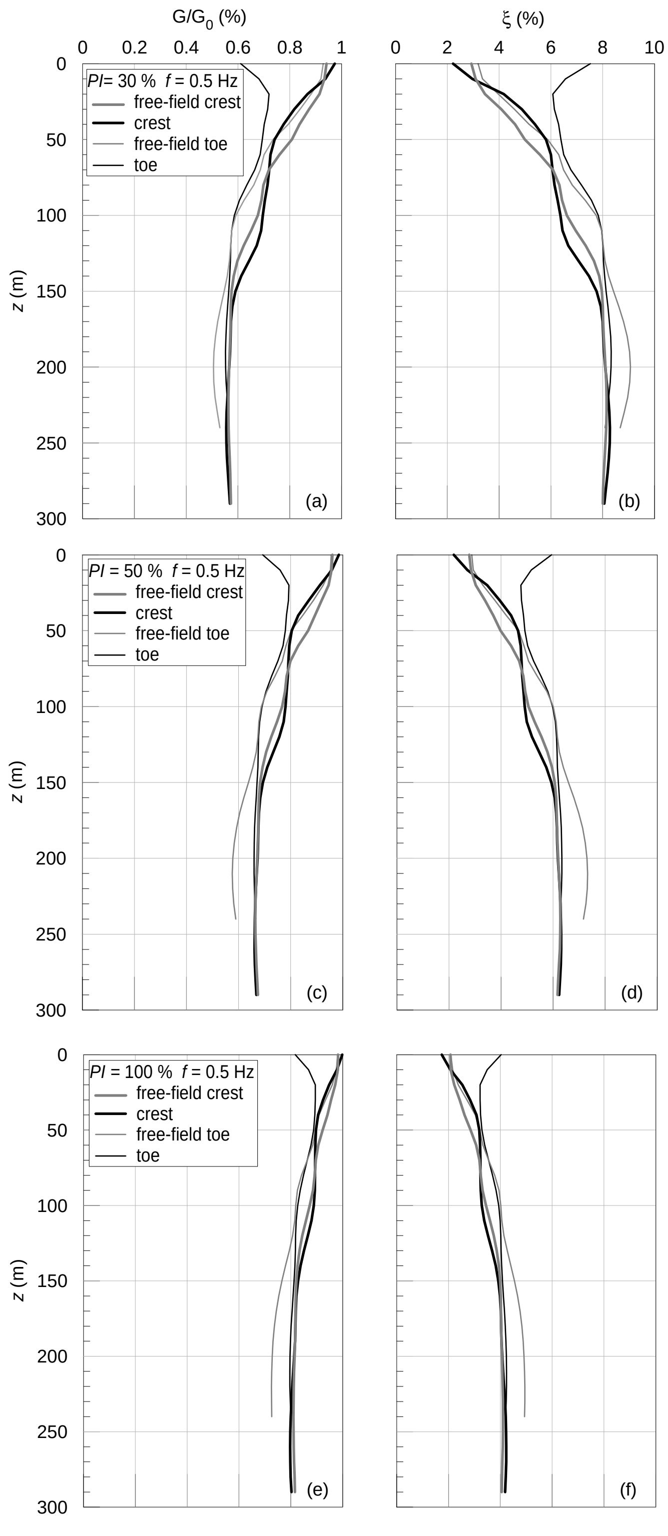

Figure 4: Profiles of the mobilized normalized shear modulus and damping ratio (i = 45°, a_0 = 0.1 g).

In Figure 4 the profiles relevant to the cases i = 45°, a_0 = 0.1g, f = 0.5 Hz and PI = 30, 50 and 100 % are plotted for the two vertical boundaries of the *FE* model (*free-field* condition) and for the verticals through the crest and the toe of the slope. From all the plots the effect of soil non-linear behaviour is apparent, being more relevant when PI = 30 and 50 % are assumed, corresponding to smaller values of the linear threshold shear strain γ_l. As an example, for PI = 30%, values of G/G_0 as small as 0.6 in the lower 100 m of the soil profile and in the range 0.6-1 in the upper portion of the profile are attained; the corresponding mobilized damping ratio, from the initial value $\xi_0 \cong 2\%$ increases with depth up to about ξ = 9 %. In all the cases of Figure 4 non-linear effects are more relevant for profiles through the toe of the slope.

Finally, the degree of nonlinearity introduced in the analysis, adopting different values of the plasticity index can be observed in the profiles of Figure 5 showing the results obtained for the case i = 45° and input frequency f equal to 0.5 Hz (Figures 5a,b) and 2 Hz (Figures 5c,d). For decreasing value of PI the effects of soil nonlinearity become more relevant and profiles of the mobilized G/G_0 and ξ typical of inhomogeneous soil deposits are obtained.

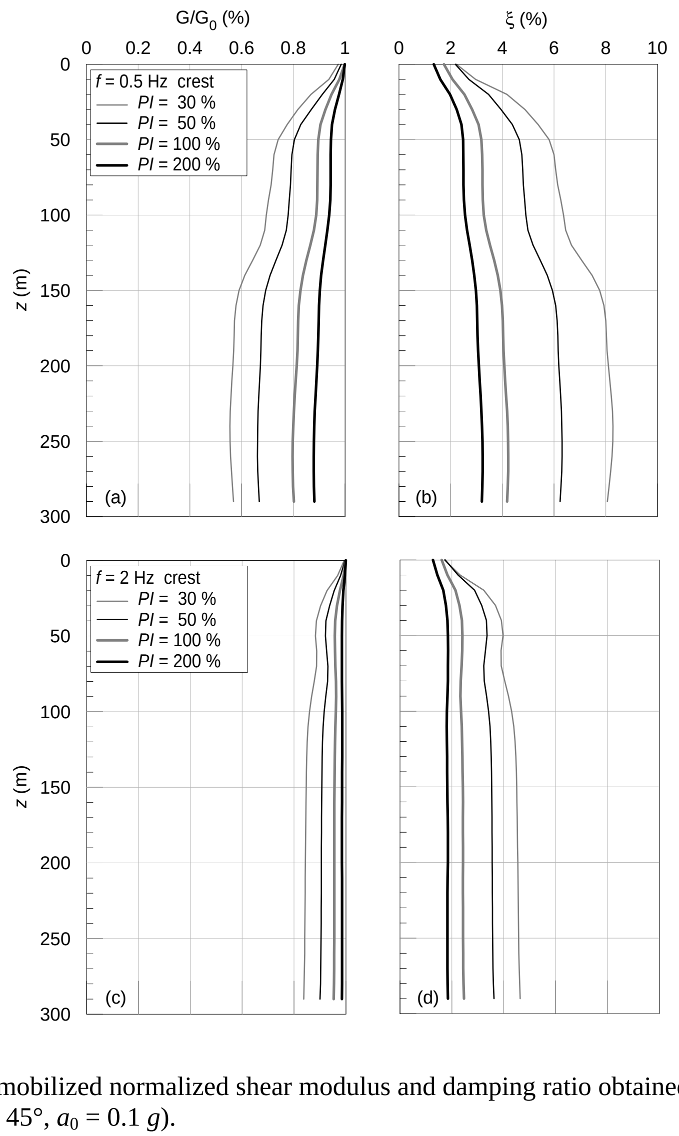

Figure 5: Profiles of the mobilized normalized shear modulus and damping ratio obtained for the vertical through the crest of the slope (i = 45°, a_0 = 0.1 g).

4 INFLUENCE OF INPUT MOTION FREQUENCY

To investigate the influence of the frequency of the input motion on the slope response, *EL* analyses were carried out assuming a_0 = 0.1g and f in the range 0.5-10 Hz; moreover, to fully capture the effect of frequency, the plasticity index PI was varied in the range 30-200% (Table 1).

The results obtained for the whole range of the considered input frequencies (0.1÷10 Hz) and for all the considered values of *PI* (30÷200 %) are synthetically shown in Figure 6 where the horizontal and the vertical topographic amplification factors are plotted against the normalized frequency H/λ. For $PI = 100$ and 200 % the response of the system is approximately linear regardless the values of *f* (Figures 4e,f and Figure 5). In these cases, such as for the linear system, the stratigraphic effects prevail on the computed response because the input frequencies are practically coincident with the natural frequencies estimated for the linear system; with the only exception of $f = 0.5$ Hz ($H/\lambda = 0.05$), for which the curves of A_h (Figure 6a) exhibit a peak, the horizontal topographic amplification factor A_h is close to or below unity for both values of *PI*.

For lower values of plasticity index ($PI = 30\%$, 50%) the effect of soil non linear behaviour is not negligible (Figure 4a-d, Figure 5) and the values of A_h increase especially for the case $PI = 30\%$.

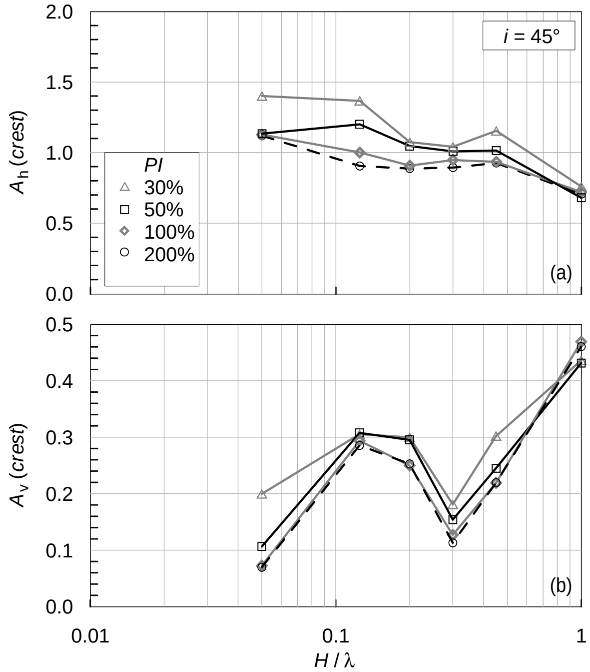

Figure 6: Horizontal (a) and vertical (b) topographic amplification factors at the crest of the slope ($i = 45°$, $a_0 = 0.1\ g$).

Concerning the vertical topographic amplification factor, the plots of Figure 6b show that A_v varies significantly with the normalized frequency H/λ but it is not appreciably affected by the plasticity index (with the only exception of the case $PI = 30\%$).

Moreover, it is worth noting that the results commented above were obtained in the case $a_0 = 0.1$ g, however, as a consequence of non-linear soil behaviour, different results would possibly be obtained for different amplitudes of the input motion.

As it is usual for non-linear systems [23, 24, 25], the actual slope response cannot be predicted *a priori* since it depends on all the factors (a_0, f, G_0, ξ_0, PI) affecting soil non-linear behaviour.

Once more, it is confirmed that due to coupling between stratigraphic and topographic effects a proper evaluation of topographic amplification should, in principle, require specific non-linear *2D* analyses.

5 CONCLUDING REMARKS

This paper describes the results of *2D* numerical *FE* seismic response analyses carried out to investigate, under different assumptions, the seismic response of slopes subjected to vertically propagating *SV* waves.

Different sets of analyses were carried out focusing on slopes overlying a compliant bedrock, assuming that soil behaves as an equivalent-linear visco-elastic material. The amplification of the ground motion was evaluated in terms of topographic amplification factors.

The effect of soil non-linear behaviour was investigated varying the range of shear strains in which soil responds linearly by changing the relationship adopted to describe the variation of normalized shear modulus and damping ratio with induced shear strain; the influence of the amplitude and of the frequency of the input motion was also analyzed.

The results demonstrate that topographic amplification is affected by the non-linear behaviour of the soil. Specifically, horizontal and vertical topographic amplification factors were found to depend on the tendency of soil to exhibit a non-linear behaviour and on the degree of non-linearity arising in its seismic response. These, on turn, are related to all the factors affecting non-linear dynamic response: soil stiffness and damping ratio at small strain, characteristics of the input motion and non-linear stress-strain relationship.

The results also confirmed the expected complex interaction between topographic and stratigraphic effects and highlighted that their reliable evaluation cannot be performed through a decoupled approach and require a non-linear *2D* seismic response analyses.

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