Numerical Evaluation of Slope Topography Effects on Seismic Ground Motion

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Abstract— **This paper presents results of numerical analyses for the seismic response of step-like ground slopes in uniform visco-elastic soil, under vertically propagating SV seismic waves. The aim of the analyses is to explore the effects of slope geometry, predominant excitation frequency and duration, as well as dynamic soil properties in a parametric manner, and provide qualitative as well as quantitative insight to the phenomenon. Among the main conclusions, we stress that this kind of topography may lead to intense amplification or de-amplification variability at neighboring (within a few tens of meters) points behind the crest of the slope, especially for high frequency excitations. Nevertheless, for the horizontal motion a general trend of amplification near the crest and de-amplification near the toe of the slope seems to hold. As a result of these two findings, it becomes evident that reliable field evidence of slope topography aggravation is extremely difficult to establish. Finally, our study shows the generation of a parasitic vertical component of motion in the vicinity of the slope, due to wave reflections at the slope surface, that under certain preconditions may become as large as the horizontal.**

Keywords—**earthquakes, topography effects, slopes, numerical analyses**

INTRODUCTION

The effect of step-like slope topography on seismic ground motion has not been thoroughly examined in the literature, despite that there is indisputable evidence of its significance even from the late 1960's [1]. In fact, this form of surface topography has drawn the least attention among scientists, as compared to hills and canyons, despite its significance in engineering practice. One possible reason is the non-symmetric geometry of step-like slopes, which complicates analytical solutions, and favors mostly site-specific numerical simulations that are difficult to generalize. Another reason could be the fact that conclusive results from field measurements are difficult to obtain, due to the wave scattering that a step-like slope produces, as discussed later in this paper. As a result, approximate relations and design guidelines are rare, while relevant provisions have not yet been implemented in the majority of the modern seismic codes.

Among the published studies, the majority concerns specific geometries and seismic excitations (e.g. [1], [2], [3], [4], [5], [6]), or examine specific aspects of the phenomenon such as the wave scattering generated at the vicinity of the slope [7], or the effects of a soft soil cap in the area of the slope [8]. The only systematic parametric study found in the literature is that by [9] and [10], which provides valuable insight to the effects of slope inclination i and height H, wave type (P, SH and SV) and propagation length λ, as well as the angle of wave incidence β. Nevertheless, the results of the analyses are presented solely at the crest and at distances equal to H, 2H and 4H behind it. Furthermore, they do not address the effect of two factors that are commonly accounted for in most seismic ground response analyses: the hysteretic damping ratio of the soil ξ and the duration of the shaking or the number of equivalent uniform excitation cycles N. Thus, the presented results cannot be readily used for a quantitative assessment of the effect of slopes, in the form of either simple approximate relations or seismic code provisions.

Aiming at this goal, preliminary results are presented from an extensive parametric study of step-like slope topography effects, performed with the Finite Difference method. The relevant research was triggered from recent evidence that such effects played an important role in the extent of damage caused by two recent destructive earthquakes in Greece ([3], [4], [11] and [6]): the 1995 Aegion and the 1999 Athens events. Compared to the study by [9] and [10], our study is narrower in the sense that it focuses merely on the case of vertically propagating SV waves. On the other hand, it explores in detail the effects of a larger number of problem parameters and provides a continuous assessment of slope topography effects along the ground surface, for a sufficient length behind the crest and in front of the toe of the step-like slope. It should be underlined, that the quantitative assessments hereby provided apply conservatively to SH waves as well, since SH topographic amplification has been shown smaller than that of SV waves ([9], [10]).

METHODOLOGY OUTLINE

The numerical analyses were performed with the Finite Difference method [12], for linear visco-elastic soil. A schematic presentation of the analyzed geometry and the boundary conditions is provided in Fig. 1. More specifically,

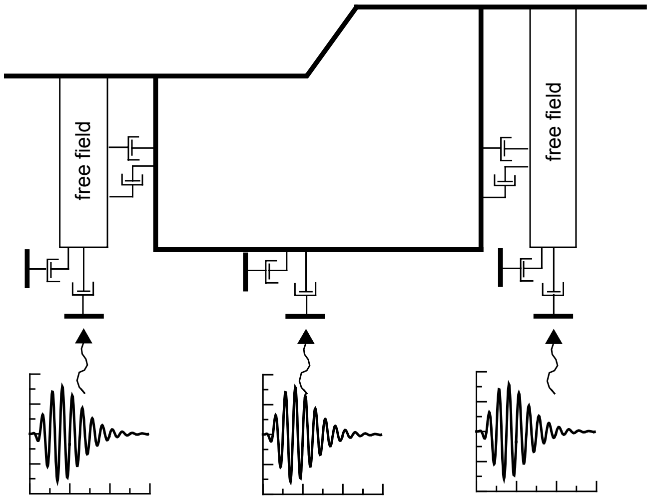

Fig. 1: Schematic illustration of finite difference model for step-like surface topography, the applied boundary conditions and examples for the incoming Chang's signal – type time histories

- 28,000 to 120,000 quadratic elements were used to simulate the soil mass, with a maximum height equal to 1/10 ÷ 1/20 of the predominant wavelength of the seismic excitation, so that the numerical distortion of its frequency content was avoided.
- The width and the height of the analyzed geometry were usually set at *20H* and *5H* respectively, so that the effect of waves artificially reflected at the boundaries is minimized.
- For the same purpose, transmitting boundaries were applied at the base of the geometry, while boundaries simulating the free field were applied at its right and left sides.

The seismic excitation was applied at the base of the analyzed soil section as stress, rather than displacement (or acceleration) time history. Most of the parametric analyses were performed either with a harmonic excitation of 20 – 40 uniform cycles, or with a Chang Signal excitation aimed to simulate the limited duration as well as the gradual rise and decrease of shaking amplitude (see Fig. 1 for form of Chang's signal). In addition, a limited number of parametric analyses were performed with actual seismic excitations, obviously containing much wider frequency content.

The overall accuracy of the numerical methodology was checked through comparison with analytical solutions for the seismic response of the ground surface across half-circle shaped canyons, for uniform ground and vertically propagating harmonic SV waves [13]. The results of this study were chosen for two reasons: in lack of analytical results for step topography and due to the fact that they are well established and commonly used for calibration of new methods or studies in the literature. A typical comparison between numerical and analytical predictions for the horizontal (U_h) and the (parasitic) vertical (U_v) components of the peak ground surface displacement is shown in Fig. 2, for the particular case of canyon radius R=25m and wavelength ratio λ/R = 2.

It is important to notice that the numerical methodology previously outlined does not take consistently into account the effect of soil non-linearity. Namely, shear moduli remain constant (elasticity) and material damping is of the Rayleigh type, i.e. it is frequency dependent and the reference damping each analysis is the damping value for the frequency of the excitation. For this reason, as well as for the benefit of generalization, the results of the numerical analyses are not evaluated directly, but following normalization against the free-field response of the ground, which is free from any topography effects. For this purpose, each basic 2-D analysis was supplemented by two 1-D analyses: one for the free field in front of the toe of the slope and the other for the free field behind its crest. This approach is cumbersome, but more accurate than evaluating the free-field response from the results of the 2-D analyses alone (at nodes at large distance away from the slope). The reason is that topography effects decrease asymptotically with distance from the slope and may not completely disappear within the analyzed geometry, thus underestimating the overall amplification effects.

TYPICAL RESULTS

Typical results from the numerical analyses are presented in Fig. 3, for the specific case of uniform soil, slope inclination $i = 30^o$, normalized height $H/\lambda = 2.0$, critical damping ratio ξ = 5% and six significant cycles of base excitation (N = 6). This figure shows the variation of the topography aggravation factors $A_h=a_h/a_{h,ff}$ and $A_v=a_v/a_{h,ff}$ with distance from the crest x, where a_h and a_v denote the peak horizontal and vertical accelerations at the ground surface.

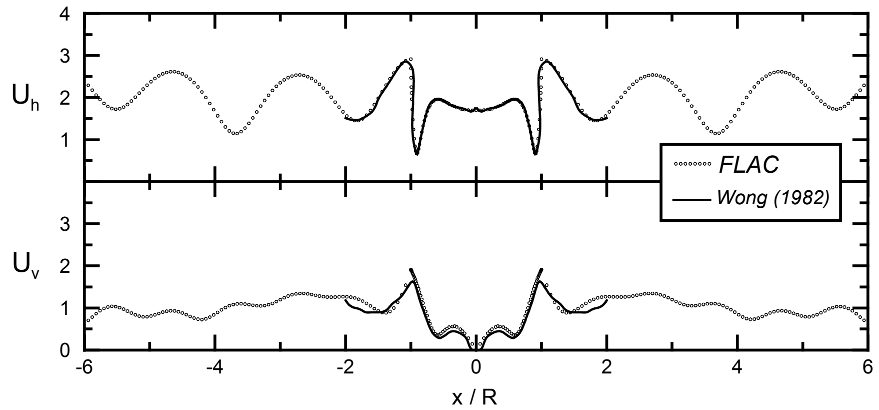

Fig. 2: Analytical verification of numerical scheme for canyon topography (for vertical SV wave, R=25m, λ/R=2)

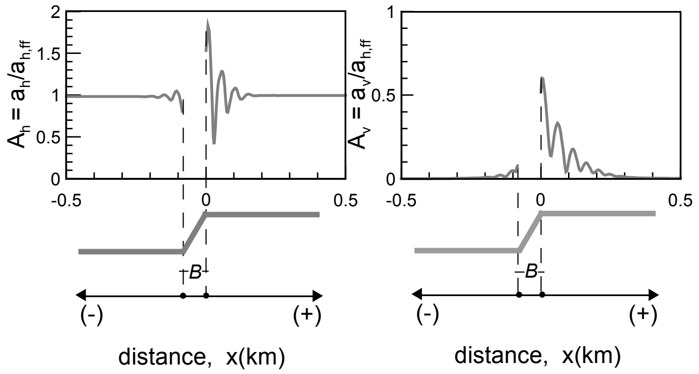

Fig. 3: Typical results for the topographic amplification of the peak horizontal A_h and the parasitic vertical A_v acceleration, as a function of horizontal distance x from the crest (results for H/λ=2, i=30°, N=6, ξ=5%)

Parameter $a_{h,ff}$ denotes the free-field value for the horizontal direction and is used for normalization of both a_h and a_v, since $a_v = 0$ for a vertically propagating SV wave in a uniform soil. Review and interpretation of this figure alone may provide insight to the mechanisms, which control topography effects and lead to some first conclusions of practical interest. Namely:

(a) Even a purely horizontal excitation, as a vertically propagating SV wave, results in considerable (parasitic) vertical motion at the ground surface. This component of ground motion is independent from any vertical excitation induced by the earthquake to the base of the slope and, consequently, it has to be superimposed to it. The results of the parametric analyses show that the vertical component of seismic motion may reach the same order of the horizontal free-field motion.

(b) The topography aggravation of the horizontal ground motion, expressed through the acceleration ratio $A_h = a_h/a_{h,ff}$, fluctuates intensely with distance away from the crest of the slope, alternating between amplification ($A_h > 1.0$) and de-amplification ($A_h < 1.0$) within very short horizontal lengths. For the typical results of Fig. 3, this length is approximately 25m, i.e. H/2. This finding implies that the experimental verification of topography effects through inverse analysis of structural damage is very far-fetched, and that actual ground motion recordings near slopes must be obtained via very dense seismic arrays.

(c) It is also worth noticing that the horizontal ground motion is de-amplified at the toe of the slope and amplified near the crest. As a result, topography aggravation may be seriously overestimated, when measured as the peak seismic ground motion at the crest versus that at the toe of the slope. For example, for the results of Fig. 3, this procedure would give $A_h \simeq 1.70 / 0.80 = 2.13$, which is considerably higher than the peak topography aggravation behind the crest $A_{h,max} = 1.83$. This overestimation may reach 100% for steeper slopes (see Fig. 5) and may explain, at least in part, why field measurements (without appropriate free field selection) of topography aggravation are significantly higher than analytical predictions [14].

Findings (a) and (b) above can be readily attributed to the reflection of the incoming SV waves on the inclined free surface of the slope (Fig. 4), which leads to reflected P and SV waves impinging obliquely at the free ground surface behind the crest, as well as Rayleigh waves.

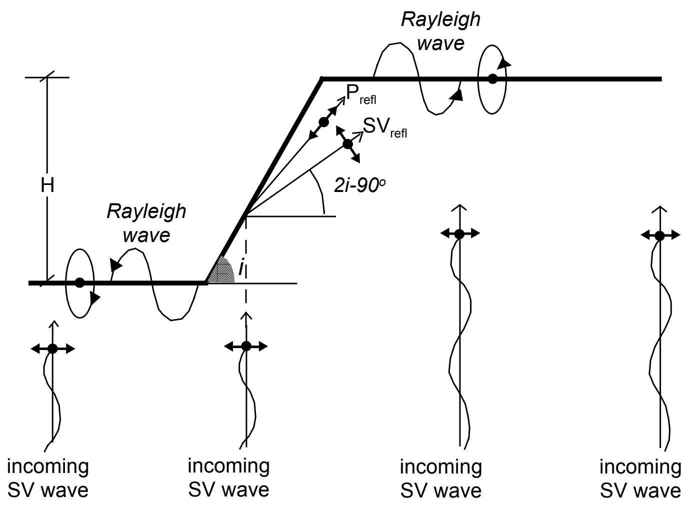

Fig. 4: Schematic illustration of incoming SV waves and induced P_{refl}, SV_{refl} and Rayleigh in the case of steep step-like slopes ($i \geq 45^o$)

All these induced waves have a strong vertical component. In addition, they arrive with a time lag and a phase difference at the different points of the ground surface so that their superposition to the incoming SV waves may lead either to amplification or to de-amplification of the horizontal seismic motion.

PARAMETRIC ANALYSES

In all, 109 parametric analyses were performed in order to quantify the effect of the following *potentially* important parameters:

- the slope inclination i,
- the normalized height of the slope H/λ, where λ denotes the predominant wave length of the incoming SV waves,
- the number of significant excitation cycles N, defined for a stress level equal to the 1/2 of the peak,
- the critical hysteretic damping ratio ξ,
- the variation of dynamic shear modulus with depth, and
- the frequency breadth of the seismic excitation.

The first four of the above parameters were investigated thoroughly, with the aid of 90 from the total of 109 parametric analyses, so that their effect can be expressed by means of approximate relations. On the contrary, the remaining two parameters were the subject of preliminary investigation, aimed at a mere qualitative evaluation of their importance.

The effects of i, H/λ, N and ξ is demonstrated in Figures 5 to 8, using the same format as in Fig. 3. In broad terms, it is observed that the slope inclination and the normalized height of the slope have a significant effect on the aggravation of the horizontal and vertical ground motion (factors A_h and A_v), as well as on the distance to the free field in front and behind the slope. On the contrary, the hysteretic damping ratio of the soil has a significant effect only on the distance to the free field, while the number of significant excitation cycles has a minor overall effect.

The statistical analysis of the results from all parametric analyses has not been yet finalized. Nevertheless, it is safe to report that, for common conditions of practical interest (i.e. H/λ = 0.2÷1.0, i = 25÷75° and ξ = 5÷15%),

(a) the range of computed values for the peak horizontal and vertical aggravation factors behind the crest are $A_{h,max}$ = 1.20 ÷ 1.50 and $A_{v,max}$ = 0.10 ÷ 1.10, while
(b) the distance to the free field is D_{ff} = (2 ÷ 8)H.

From an engineering point of view, this study assumes that *free field* conditions are observed when both $A_h \leq$ 1.10 and $A_v \leq$ 0.10 apply.

The above values of $A_{h,max}$ and $A_{v,max}$ are broadly comparable to the provisions of the European and the French seismic codes, EC-8 (2000 & draft 2002) and AFPS [15], which require 20% and 40% increase respectively of the peak horizontal acceleration at the most. However, the distance to the, above defined, free field is significantly larger than that mentioned in these codes. Namely, the EC-8 (2000 & draft 2002) requires vaguely that peak horizontal accelerations are increased "*near the top edge*", while the explicit evaluation of the distance to the free field provided by [15] does not exceed the height of the slope H. These distance estimates remain very short even if the limits of the topography aggravation factors for the free field are increased to $A_h \leq$ 1.20 and $A_v \leq$ 0.20. Furthermore, it should be noted that current seismic codes do not contain any provisions for parasitic vertical motion, or a correction factor for the vertical elastic response acceleration spectra.

As mentioned above, the effects of soil layering and the breadth of frequencies of actual seismic excitations were not investigated thoroughly, but on the basis of a limited number of analyses.

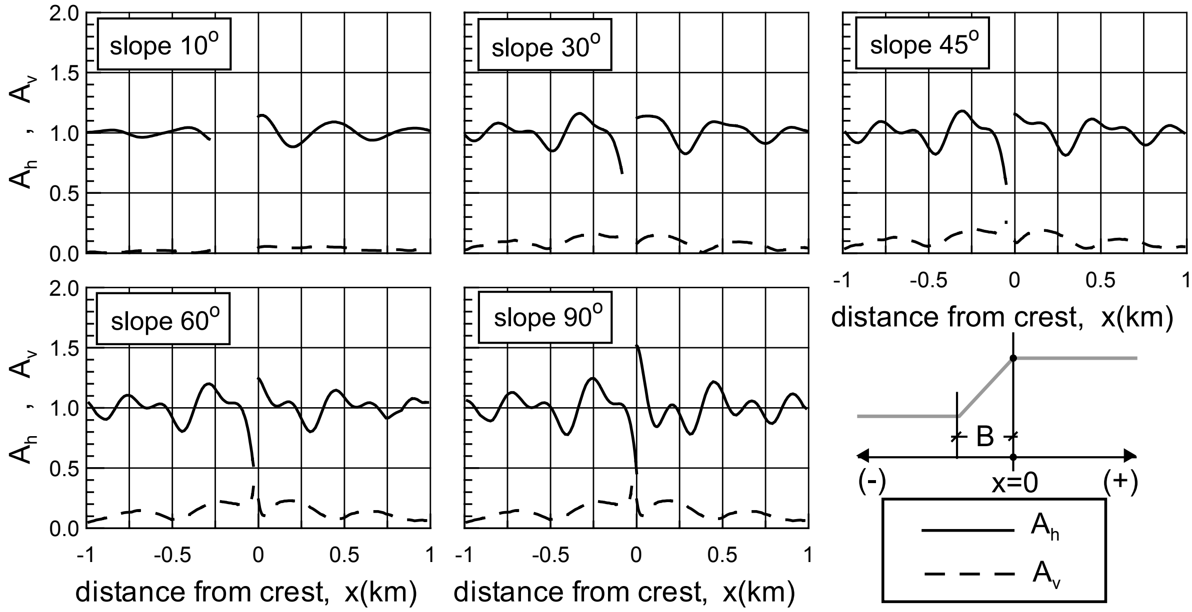

Fig. 5: Effect of slope inclination *i* on the amplification of peak horizontal A_h and parasitic vertical A_v acceleration, as a function of distance x from the crest of a step-like slope (results for H/λ = 0.2, harmonic motion and ξ < 5%)

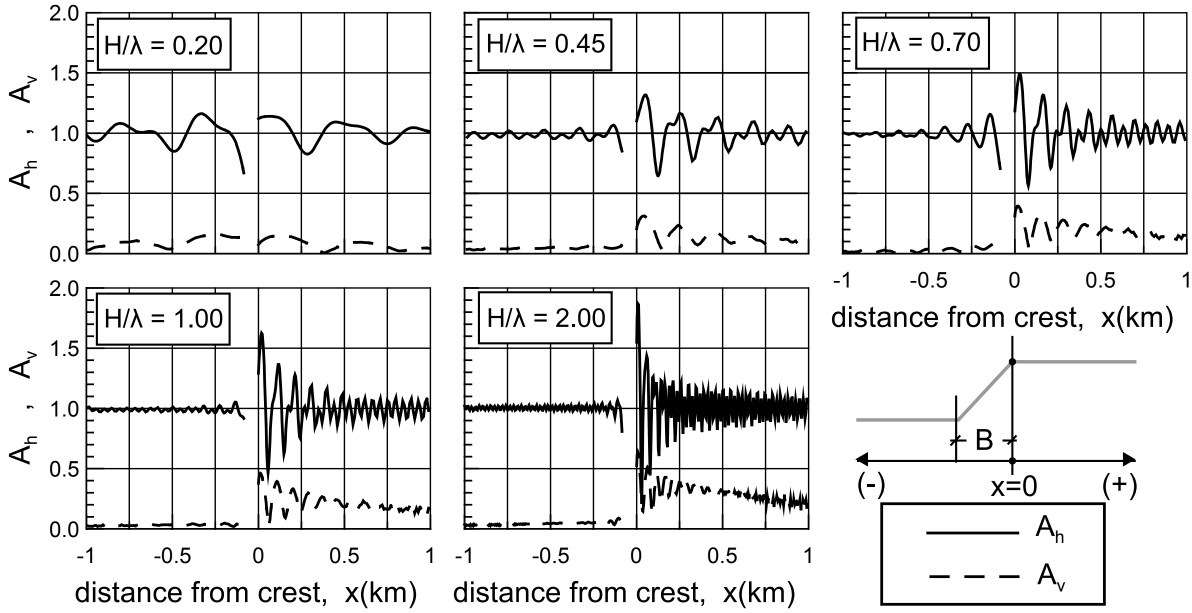

Fig. 6: Effect of normalized height H/λ on the amplification of peak horizontal A_h and parasitic vertical A_v acceleration, as a function of distance x from the crest of a step-like slope (results for i=30°, harmonic motion, ξ < 5%)

In brief, these analyses show that the existence of bedrock below the slope has an important effect on the resulting topography aggravation that cannot always be decoupled from effect of free-field site period as suggested by [10]. On the contrary, the finite breadth of frequencies of actual seismic excitations, as compared to the practically single frequency of the Chang's signal excitation that was used in the parametric analyses, appears to be less important and does not restrict the validity of the findings stated above.

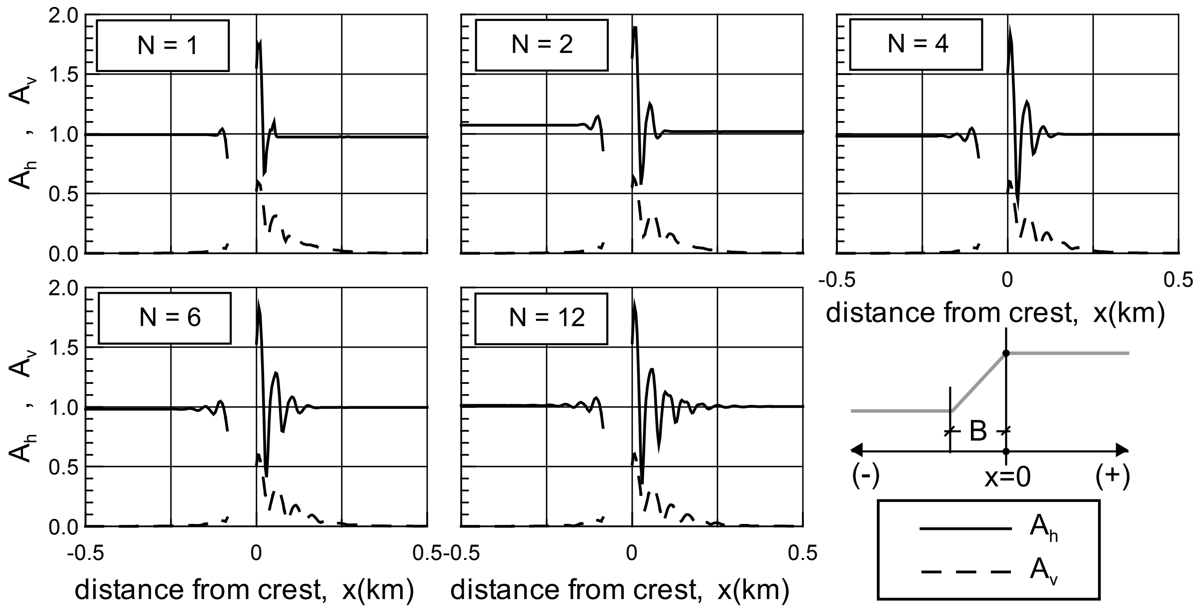

Fig. 7: Effect of number of significant cycles N on the amplification of peak horizontal A_h and parasitic vertical A_v acceleration, as a function of distance x from the crest of a step-like slope (results for $H/\lambda = 2$, i=30° and $\xi = 5\%$)

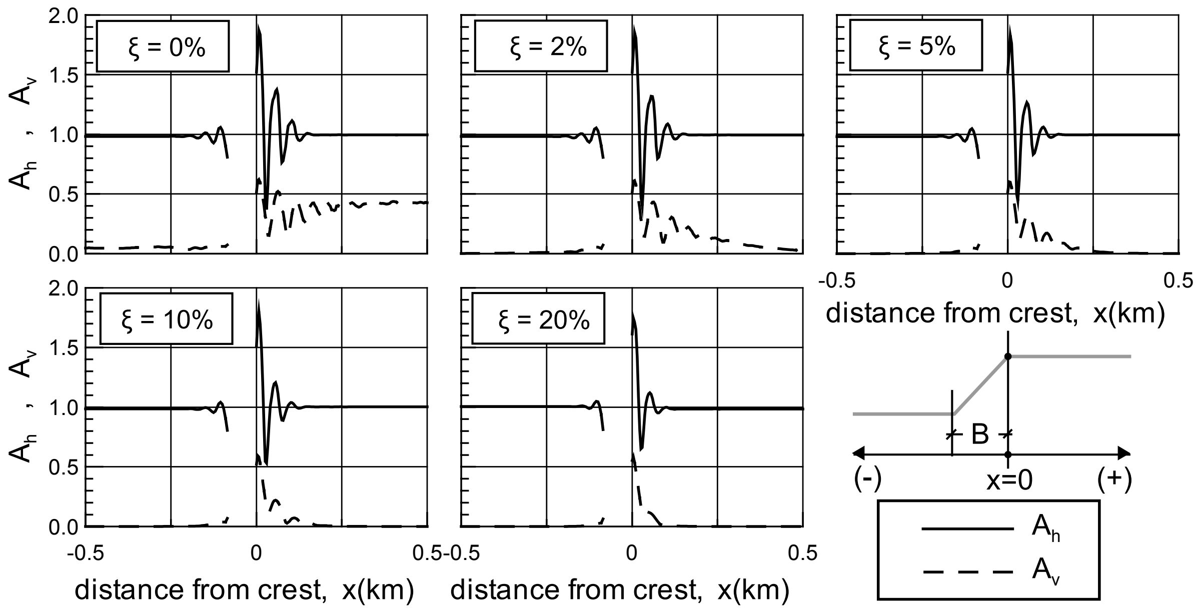

Fig. 8: Effect of number of soil damping ξ on the amplification of peak horizontal A_h and parasitic vertical A_v acceleration, as a function of distance x from the crest of a step-like slope (results for $H/\lambda = 2$, i =30° and $N = 4$)

SUMMARY OF MAIN FINDINGS

The main findings of practical interest that have emerged so far from this numerical study of topography effects are the following:

(a) The effect of slope topography is to alter (amplify or de-amplify) the peak horizontal seismic ground acceleration in front and behind the crest and also to produce a parasitic vertical acceleration that has to be added to that of the original seismic excitation.

(b) The peak values of topography aggravation factors for the horizontal and vertical ground acceleration behind the crest usually vary between $A_{h,max} = 1.20 \div 1.50$ and $A_{v,max} = 0.10 \div 1.10$ respectively, while free field conditions behind the crest are usually met at a distance $D_{ff} = (2 \div 8)$H.

(c) Topography effects fluctuate intensely with distance away from the slope, so that detecting them on the base of field measurements alone becomes a very demanding task.

(d) The few seismic codes that deal with slope topography aggravation are reasonable with regard to the increase of peak horizontal accelerations. Nevertheless, they oversee the production of parasitic vertical acceleration and dangerously underestimate the distance from the slope where topography effects become negligible.

At present, our research is focused on the statistical analysis of the relevant data, with the aim to establish simple approximate relations and a theoretically consistent set of seismic code provisions for the evaluation of slope topography effects. It is certainly acknowledged that the lack of experimental evidence, to compare with and calibrate the numerical findings, will be a serious obstacle in our effort. However, it appears that this is an objective difficulty that should be indirectly accounted for at present, by increased conservatism in the compilation of the results from the parametric analyses, and by additional well-planned field research in the future.

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