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AGGRAVATION OF THE PEAK SEISMIC ACCELERATION IN THE VICINITY OF 2D HILLS, CANYONS AND SLOPES

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ABSTRACT

This paper studies the topographic aggravation of the peak seismic acceleration in the horizontal and vertical directions for various cases of 2D uniform surface geometries: hills, canyons and slopes. The study is based on a large number of 2D wave propagation analyses for uniform soil conditions performed with the finite-difference method. All analyses were visco-elastic, assumed vertically impinging harmonic SV waves and studied parametrically the effects of the slope inclination i, the dimensionless height H/λ of the topographic feature (where H is the height and λ is the predominant S wavelength) and of the width B of the canyon base and the hill top. The analyses show that the crests of canyons suffer from increased parasitic vertical accelerations as compared to the respective slopes (with the same ι and H/λ), while the aggravation of the horizontal acceleration is similar. For the cases of hills, the analyses show that the width B of the hill top is a crucial parameter, since small values of B lead to very large aggravations of the peak horizontal acceleration at the hill crest, as compared to the respective slopes.

INTRODUCTION

The effect of surface topography on seismic ground motion has been repeatedly shown to be detrimental to structures. Earthquakes like the San Fernando 1971 (Boore 1972), Friuli 1976 (Brambati et al 1980), Irpinia 1980 (Castellani et al 1982), Coalinga 1983 (Celebi 1991), Chile 1985 (Celebi 1991), Whittier Narrows 1987 (Kawase and Aki 1990), Northridge 1994 (Ashford and Sitar 1997), Aigio 1995 (Bouckovalas et al 1999), Armenia 1999 (Restrepo & Cowan 2000), Athens 1999 (Assimaki et al 2005) have shown concentration of heavy damage mainly near the crest of topographic irregularities, such as hills, canyons or slopes. Nevertheless, the foregoing observations are indirect indices of topographic aggravation of seismic ground motion. Actual field measurements of this phenomenon have been performed, but mostly concern small amplitude events or noise, since these have been recorded by sensors usually deployed after large events (see Geli et al 1988, Bard 1999 for review). There are, of course, exceptions to this rule, but these are relatively few (e.g. Tarzana hill during the Northridge 1994 earthquake, Bouchon & Barker 1996). Yet, reliable conclusions based on field measurements alone are not easy to be derived for various reasons (e.g. un-availability of free field recording for proper normalization of recordings, non-uniformity or insufficient knowledge of soil conditions that impede the distinction of soil from topography effects, sparsity of sensors to fully record the intense spatial variability of topographic aggravation even for uniform soil conditions).

Based on all the above, the solution for studying topographic aggravation has been mostly given by analyses, performed either numerically (e.g. finite element method: Assimaki et al 2005, finite difference method: Bouckovalas & Papadimitriou 2005), or by using analytical or semi-analytical/semi-numerical methods (e.g. Sills 1978, Sanchez-Sesma et al 1982, Bard 1982) that unavoidably employ various simplifications (e.g. uniform soil, harmonic excitations consisting of purely P, SV or SH waves). Despite the numerous pertinent studies, the issue of topographic aggravation of seismic ground motion is still unresolved, mainly because a large majority of the studies are case-studies and their results are difficult to generalize. Moreover, while being a multi-parametric problem, few of the published studies are of a parametric nature.

This paper aids at closing this gap, by parametrically analyzing and comparing the topographic aggravation for various 2D topographic shapes in uniform soil under the same excitation characteristics. In particular, of interest here are 2D slopes, and trapezoidal canyons and hills. The parametric analyses are performed for the important problem parameters highlighted in the literature survey that follows, which is performed separately for each topographic shape.

LITERATURE SURVEY

Topographic aggravation of 2D canyons in uniform soil

The study of the topographic aggravation of 2D canyons practically initiates from the seminal works of Trifunac (1971, 1973) and Wong & Trifunac (1974), who studied the effects of P and SV waves on semi-circular and semi-elliptical canyons. Later on, Wong (1982) studied parametrically the topographic aggravation of semi-elliptical canyons under P, SV and Rayleigh waves, while Chuhan & Chongbin (1988) did the same for semi-circular canyons under SH waves. The foregoing canyon shapes were selected mostly because of their benefits for facilitating the analytical study and shed important light to their topographic aggravation of canyons. Yet, more realistic canyon shapes (i.e. triangular or trapezoidal) were first analyzed by Chuhan & Chongbin (1988) with regard to SH waves, whereas Zhao & Valliappan (1993) extended the study to impinging P and SV waves. Based on these last studies, important problem parameters are the slope inclination i, the incidence angle β, the width B or height H of the canyon and the wavelength λ of the impinging excitation (see Fig. 1).

Among many significant conclusions for 2D canyons, one may underline that, in general, amplification is expected behind the crest and deamplification at the toe the inclined slopes of trapezoidal canyons, that triangular canyons may well give smaller amplifications than trapezoidal canyons if the latter have larger slope inclinations and that maximum horizontal amplifications (as compared to the free-field top ground surface behind the crest, $a_{h,top}$ in Fig. 1) generally exceed 2.0 for $\beta=0^o$ (Zhao & Valliappan 1993).

Topographic aggravation of 2D hills in uniform soil

The study of the topographic aggravation of 2D hills dates back to the pioneering works of Sills (1978), Bard (1982) and Sanchez-Sesma et al (1982). Yet, it was the review paper of Geli et al (1988) who compiled results from theoretical analyses and experimental recordings that provided important insight to the problem. So far, many different shapes of hills have been studied, like semi-circular (e.g. Sills 1978), semi-cylindrical (e.g. Yuan & Men 1992), triangular (e.g. Sanchez-Sesma 1985), trapezoidal (e.g. Kamalian et al 2008). Focusing mostly on studies on triangular or trapezoidal hills, the important problem parameters are the slope inclination i, the incidence angle β, the width B or height H of the hill and the wavelength λ of the impinging excitation (see Fig. 2).

Among many significant conclusions for 2D hills, one may underline that, in general, significant amplification is expected at the top and intense deamplification at the toe of the inclined slopes of trapezoidal hills, that exceptional amplifications are observed when the impinging wavelength is comparable to the hill width and that maximum horizontal amplifications at the hill top (as compared to the free-field ground surface in front of the toe, $a_{h,base}$ in Fig. 2) may reach even exceed 3.0 for $\beta=0^o$.

Topographic aggravation of 2D slopes in uniform soil

Compared to 2D canyons and hills, slopes have attracted less attention in published literature. This could be attributed to the fact that its topographic shape lacks symmetry, making its analytical simulation more cumbersome, but also to the notion that its response is practically that of a trapezoidal canyon, at least behind its crest. Among the published studies, the majority concerns case-studies (e.g. Bouckovalas et al 1999, Assimaki et al 2005), while a few concern specific aspects of the response, like the effects of a soft soil cap (e.g. Ohtsuki and Harumi 1983). The first systematic parametric studies found in the literature are the works of Ashford & Sitar (1997) and Ashford et al (1997) who provided valuable insight to the effects of the important problem parameters: slope inclination i, normalized height H/λ (where H the slope height and λ the predominant wave length), wave type (P, SV, SH) and angle of incidence β. Later on, Bouckovalas & Papadimitriou (2005) studied parametrically the effects of i and H/λ under vertically impinging (β=0) harmonic or nearly harmonic SV waves, highlighted the importance of soil damping ξ on topographic aggravation and proposed multi-variable relations for estimating the peak topographic aggravation of the horizontal and (parasitic) vertical acceleration behind the crest of a 2D slope in uniform soil. In the sequel, Bouckovalas & Papadimitriou (2006) used the foregoing relations to propose conservative guidelines for the spatial variation of topographic aggravation in the vicinity of 2D slopes under vertically impinging SV waves and for any combination of i, H/λ and ξ (see Fig. 1)

Among many significant conclusions for 2D slopes, one may underline that parasitic vertical accelerations may obtain comparable amplitudes with the horizontal component in the close vicinity of high inclination slopes and that maximum horizontal amplifications (as compared to the free-field top ground surface, $a_{h,top}$ in Fig. 1) do not generally exceed 2.0 for $\beta=0^o$ (Bouckovalas & Papadimitriou 2005).

Summary of important problem parameters

Based on everything mentioned above, for 2D slopes, trapezoidal canyons and hills, the important problem parameters are the slope inclination i, the incidence angle β, the height H, the width B ($B \rightarrow \infty$ for slopes) and the wavelength λ of the impinging excitation. In addition, increase of material damping ξ reduces all expected amplifications, but does not alter qualitatively the response (e.g. Bouckovalas & Papadimitriou 2005). More importantly, the response of these topographic features depends on the relative magnitude of height H (or width B) as compared to the wavelength λ. In slopes, the normalization of the geometry is performed in terms of its height H, by introducing H/λ (e.g. Ashford & Sitar 1997, Bouckovalas & Papadimitriou 2005). Due to the similarity in shape, the same is performed here for 2D hills and canyons.

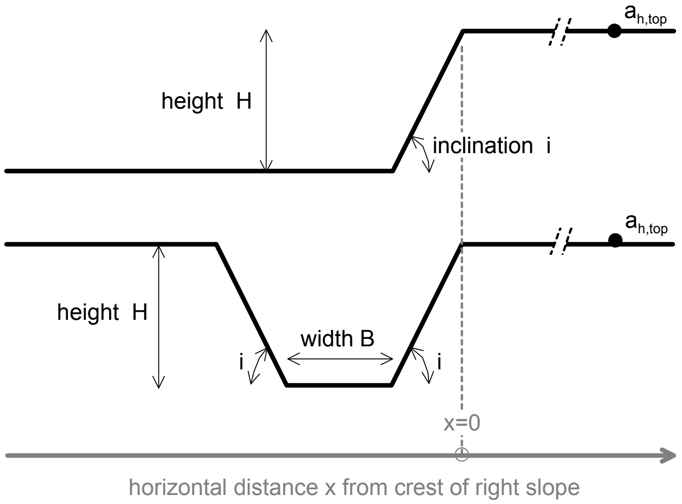

Fig. 1. Schematic illustration of 2D canyon with (inclination i, height H) and respective 2D trapezoidal symmetrical hill of width B; location of $a_{h,base}$ used in the estimation of topographic aggravation

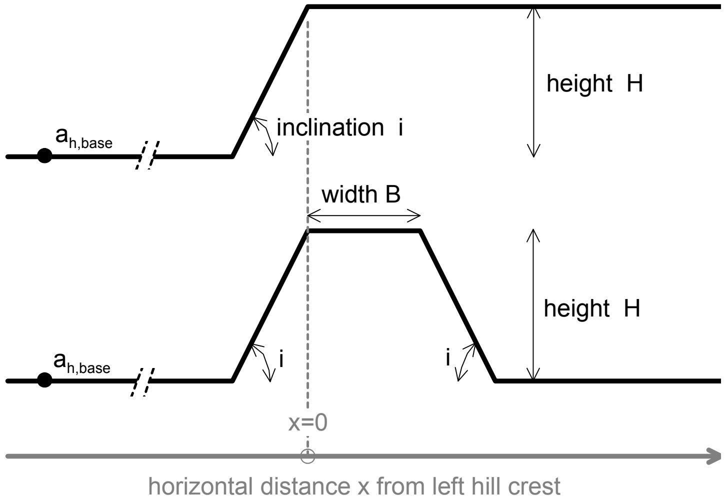

Fig. 2. Schematic illustration of 2D slope with (inclination i, height H) and respective 2D trapezoidal symmetrical hill of width B; location of $a_{h,base}$ used in the estimation of topographic aggravation

NUMERICAL METHODOLOGY

The two dimensional numerical analyses were performed with FLAC (Itasca Inc, 1998), that employs the finite difference method, for linear visco-elastic soil with shear wave velocity V_S = 500m/s, Poisson's ratio $v=1/3$ and mass density ρ = 2Mg/m^3. The hysteretic response of the soil is modeled using Rayleigh damping that had a minimum value of 5% at the period T_e of the harmonic excitation of each analysis. In all cases, the topographic feature had a height H = 50m and the mesh extended to horizontal distances 1000m (=20H) from either side and to a depth of 500m (=10H) in order to minimize artificial reflections at the boundaries. For the same reason, the lateral mesh boundaries were equipped with free-field boundaries that simulate the 1D seismic response of horizontal ground, whereas transmitting boundaries were attached to base nodes. The seismic excitation was applied as a time history of shear stress at the horizontal base of the mesh, unlike common practice that applies time-histories of acceleration (or velocity, or displacement) and induces rigid bedrock response to the whole boundary value problem. Based on all the above, the excitation in all analyses was harmonic SV waves impinging vertically upward ($\beta=0^o$) from an underlying infinite homogeneous halfspace.

In order to generalize the seismic ground response results in terms of topographic aggravation, each 2D analysis was complemented by two 1D analyses, one for the soil column reaching the base of the topographic feature and the second for the soil column reaching its top. The two 1D ("free-field") analyses were performed using the same soil conditions and base excitation as the reference 2D analysis, and their results ($a_{h,base}$ and $a_{h,top}$, respectively in Figs 1 & 2) were used for proper normalization of the 2D seismic ground response results. This approach is cumbersome, but more accurate than evaluating the free-field response directly from the results of the 2D analysis (at locations far from the topographic feature). These because topography effects decrease asymptotically with distance from the topographic feature and may not completely disappear within the analyzed mesh.

As detailed in Bouckovalas & Papadimitriou (2005), the aforementioned numerical methodology has been verified through comparison with analytical solutions for the seismic response of the ground surface across semi-circular shaped canyons presented by Wong (1982). Hence, there is no need for repeating such a verification procedure here.

TOPOGRAPHIC AGGRAVATION NEAR CANYONS

Based on the foregoing literature survey, the topographic aggravation in the vicinity of slopes has already been parametrically studied by Bouckovalas & Papadimitriou (2005, 2006). Hence, the emphasis here was put on symmetric trapezoidal canyons, that may be considered as a set of opposite facing identical slopes (of inclination i and normalized height H/λ) at a base distance with width B (see Fig. 1). Based on this figure, it is the finite value of the width B that differentiates the seismic response of symmetric canyons from that of slopes, since the latter may be considered as canyons with $B \rightarrow \infty$. In all analyses for canyons, the topographic aggravation is estimated by dividing the 2D maximum horizontal a_h, and parasitic vertical, a_v, accelerations at all points on the ground surface with the maximum horizontal acceleration at the free field far from the canyon $a_{h,top}$ (see Fig. 1) and thus defining $A_{h,top}$ and $A_{v,top}$.

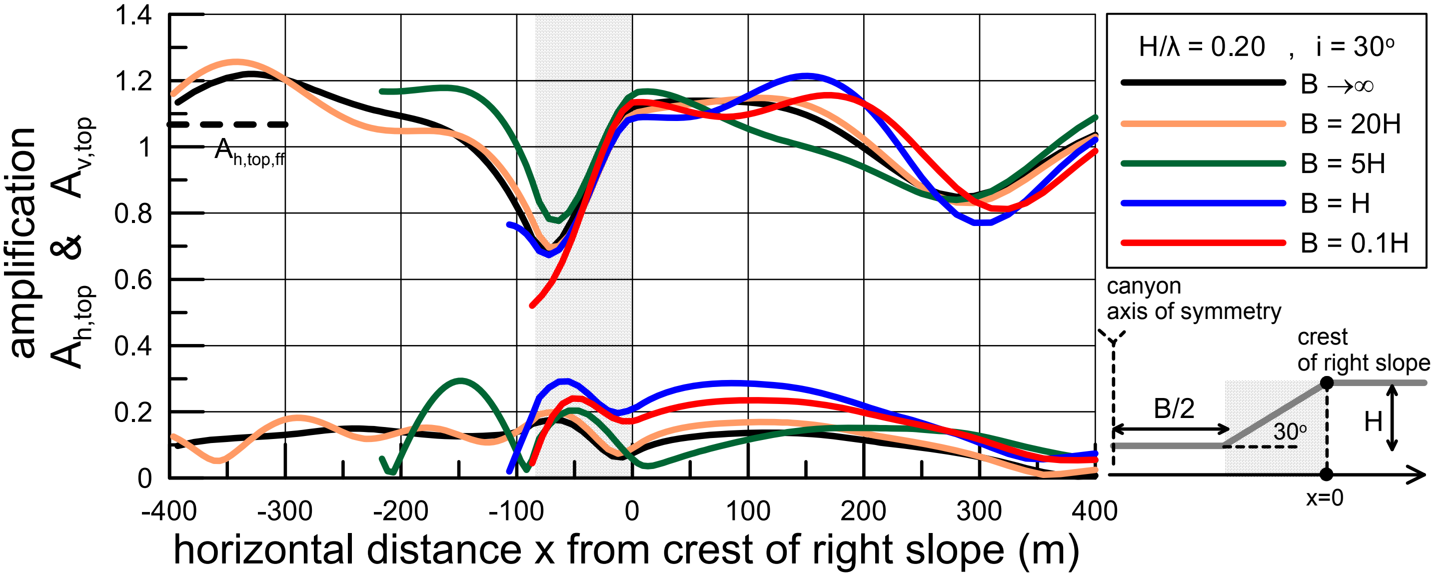

Fig. 3 Spatial variability of topographic aggravation factors $A_{h,top}$ and $A_{v,top}$ in the vicinity of symmetric trapezoidal canyons with slope inclination i=30°, normalized height H/λ=0.20 and various widths B = 0.1H, H, 5H, 20H and B→∞. Results are shown from the axis of symmetry of the canyon up to x=8H=400m behind the crest of the right slope.

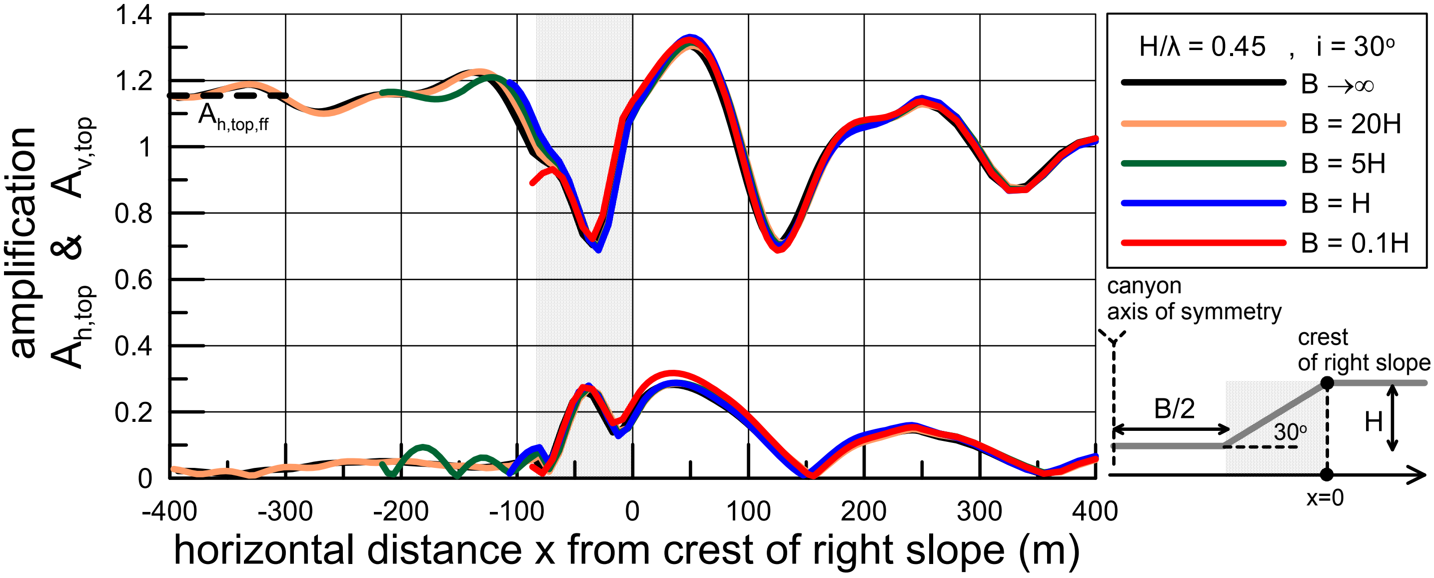

Fig. 4 Spatial variability of topographic aggravation factors $A_{h,top}$ and $A_{v,top}$ in the vicinity of symmetric trapezoidal canyons with slope inclination i=30°, normalized height H/λ=0.45 and various widths B = 0.1H, H, 5H, 20H and B→∞. Results are shown from the axis of symmetry of the canyon up to x=8H=400m behind the crest of the right slope.

Based on this train of thought, these topographic aggravation factors for canyons with finite B may be directly compared to the pertinent factors for the slope having the same inclination i and normalized height H/λ, in order to study the effect of the width B on topographic aggravation on topographic aggravation of canyons.

Hence, Figure 3 presents the variation of topographic aggravation factors $A_{h,top}$ and $A_{v,top}$ with horizontal distance from the right crest of canyons with i=30°, H/λ=0.20 and various widths B, namely B = 0.1H, H, 5H, 20H and B→ ∞. In parallel, Figure 4 shows the same comparison for canyons with i=30°, H/λ=0.45, in order to ascertain whether the conclusions from Fig. 3 hold true for higher frequency motions. Being symmetric in shape and undergoing purely vertical impinging SV waves, the seismic response of canyons is also symmetric. Hence, these figures present the variation of topographic aggravation factors $A_{h,top}$ and $A_{v,top}$ by initiating plotting from the canyon axis of symmetry and continuing towards its slope on the right side and beyond.

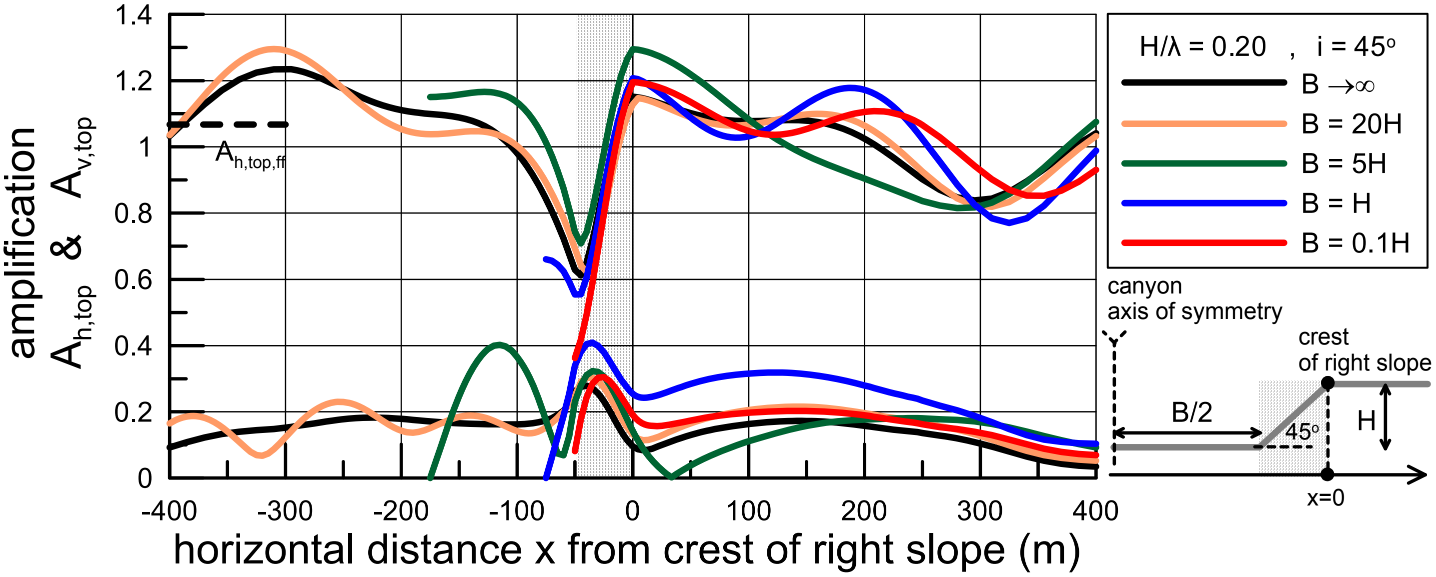

Fig. 5 Spatial variability of topographic aggravation factors $A_{h,top}$ and $A_{v,top}$ in the vicinity of symmetric trapezoidal canyons with slope inclination $i=45^o$, normalized height $H/\lambda=0.20$ and various widths B = 0.1H, H, 5H, 20H and B→∞. Results are shown from the axis of symmetry of the canyon up to x=8H=400m behind the crest of the right slope.

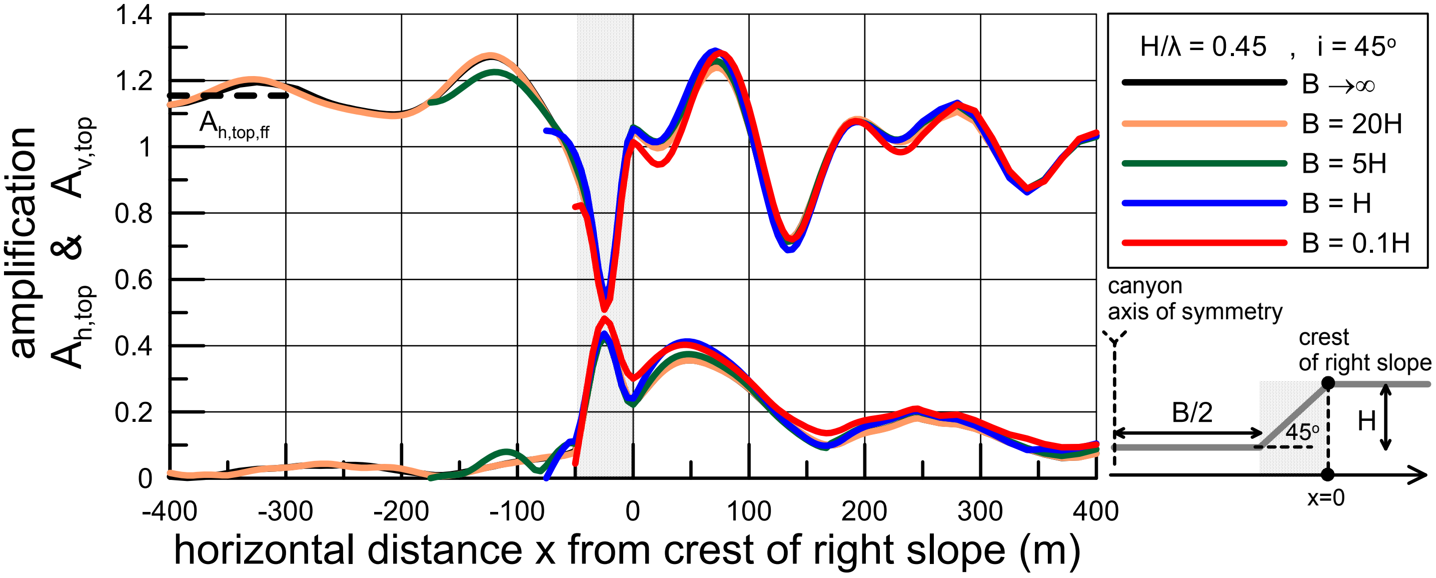

Fig. 6 Spatial variability of topographic aggravation factors $A_{h,top}$ and $A_{v,top}$ in the vicinity of symmetric trapezoidal canyons with slope inclination $i=45^o$, normalized height $H/\lambda=0.45$ and various widths B = 0.1H, H, 5H, 20H and B→∞. Results are shown from the axis of symmetry of the canyon up to x=8H=400m behind the crest of the right slope.

In order to emphasize on the seismic response in the vicinity of the inclined slope of the canyon (see shaded region), the horizontal distance is measured from the crest of the right slope of the canyon (x=0) and results are plotted until x=8H, and do not extend as far as x=20H that marks the end of the mesh. Note that based on the introduced normalization of peak accelerations, the $A_{h,top}$ at the free field behind the crest is equal to 1.0, but for the base of the canyon the 1D soil column response gives 7% (for $H/\lambda=0.20$) and 15% (for $H/\lambda=0.45$) higher peak horizontal acceleration, as denoted by the dashed line marked with $A_{h,top,ff} = a_{h,base}/a_{h,atop}$ (see Figs 1 & 2). Based on these figures:

- The response for B=20H is practically identical to that of B → ∞, meaning that a distance of 20H is practically a large enough distance to disallow the wave interaction of the opposite facing slopes, even for low frequency motions (H/λ = 0.20). On the contrary, for higher frequency motions (H/λ = 0.45), the effect of B is minimal and in practice, there is little wave interaction between the opposite facing slopes.

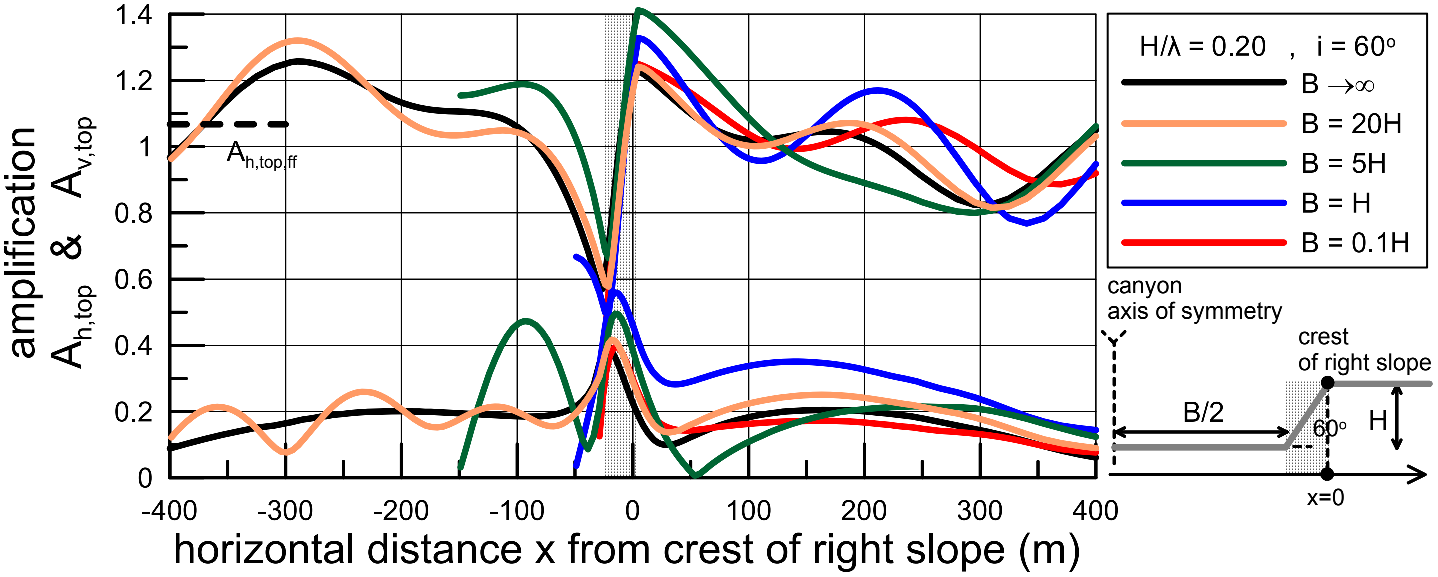

Fig. 7 Spatial variability of topographic aggravation factors $A_{h,top}$ and $A_{v,top}$ in the vicinity of symmetric trapezoidal canyons with slope inclination i=60°, normalized height H/λ=0.20 and various widths B = 0.1H, H, 5H, 20H and B→∞. Results are shown from the axis of symmetry of the canyon up to x=8H=400m behind the crest of the right slope.

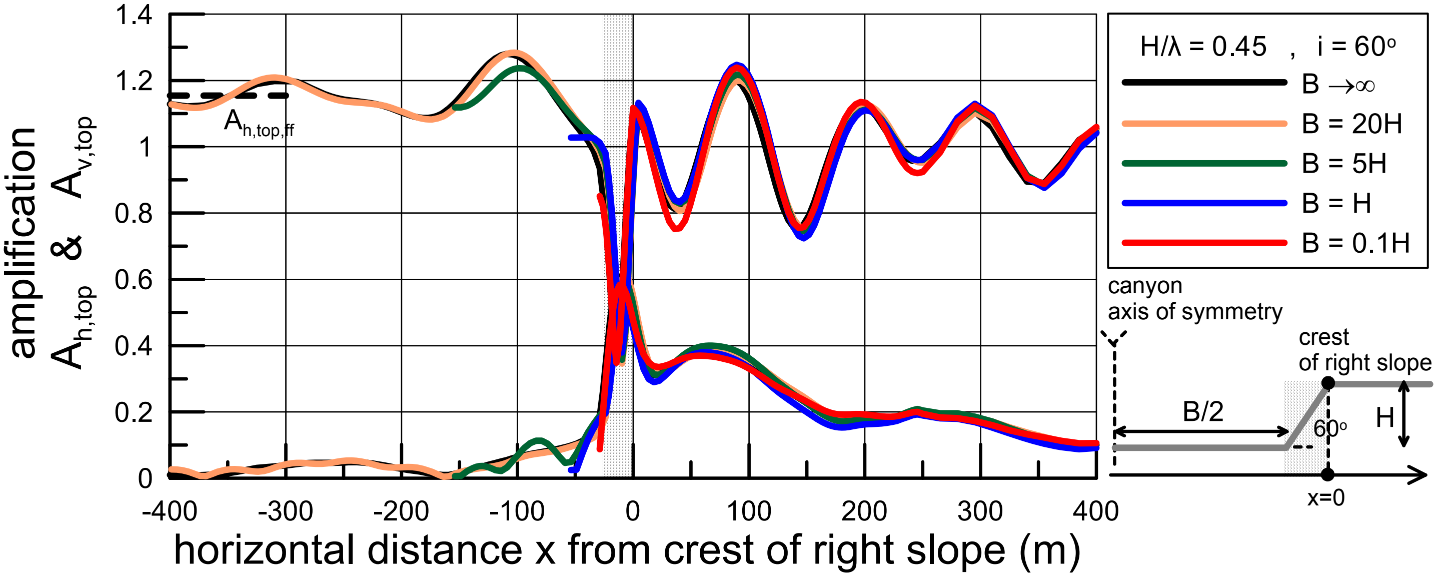

Fig. 8 Spatial variability of topographic aggravation factors $A_{h,top}$ and $A_{v,top}$ in the vicinity of symmetric trapezoidal canyons with slope inclination i=60°, normalized height H/λ=0.45 and various widths B = 0.1H, H, 5H, 20H and B→∞. Results are shown from the axis of symmetry of the canyon up to x=8H=400m behind the crest of the right slope.

- In the area immediately behind the crest, horizontal motion is generally amplified, opposite to what is observed on the inclined slope (shaded area) that is characterized by deamplification, irrespective of the width B of the canyon. Yet, at some distance in front of the toe of the slope, the canyon base may portray horizontal amplifications comparable to those behind the crest, especially if the width B is large enough (B > H) and the excitation is rich in low frequencies.
- Substantial parasitic vertical motions appear both in the area immediately behind the crest as well as on the inclined slope, irrespective of the width B of the canyon. Parasitic vertical motion is less intense at the base of canyons, especially for high frequency motions, and becomes zero at the axis of symmetry.

In order to ascertain whether the foregoing conclusions are valid for canyons with higher slope inclinations, Figs 5 and 6 present the respective results for canyons with (i=45°, H/λ=0.20) and (i=45°, H/λ=0.45), while Figs 7 and 8 do the same for canyons with ($i=45^o$, $H/\lambda=0.20$) and ($i=45^o$, $H/\lambda=0.45$). By observing these figures it may be deduced that the foregoing qualitative conclusions remain valid for higher slope inclinations. In addition, by critically reviewing all presented figures the following may be observed:

- The slope inclination i does not significantly affect the maximum horizontal amplification (i.e. maximum $A_{h,top}$) behind the crest of canyons (at least for ranging from $i=30$ to 60^o), something that is in agreement with similar results of Bouckovalas & Papadimitriou (2005, 2006) for slopes alone. Nevertheless, based on the same results for slopes, for smaller ($i < 30^o$) and larger ($i > 60^o$) slope inclinations, the maximum $A_{h,top}$ is expected to become smaller and larger respectively, something that has not been verified for canyons yet.
- On the contrary, the slope inclination i increases the maximum parasitic vertical amplification (i.e. maximum $A_{v,top}$) behind the crest of canyons (but also along the inclined slope), something that is in agreement with similar results of Bouckovalas & Papadimitriou (2005, 2006) for slopes alone. Again, based on the same results for slopes, for smaller ($i < 30^o$) and larger ($i > 60^o$) slope inclinations, the maximum $A_{v,top}$ is similarly expected to reduce and increase respectively, something that has not been verified for canyons yet.
- The spatial variability of the seismic aggravation is more intense for high frequency motions, than it is for low frequency motions, and this holds true for both canyons and slopes (see also Bouckovalas & Papadimitriou 2005, 2006). This is attributed to the Rayleigh waves travelling horizontally along the ground surface, whose wavelengths are similar to λ, i.e. the wavelength of the impinging SV waves.
- The effect of the width B on topographic aggravation is quite complex, since it does not monotonically affect the $A_{h,top}$ and $A_{v,top}$ factors. Nevertheless, its exact value is of little importance for high frequency motions ($H/\lambda=0.45$), but that is not the case for low frequency motions ($H/\lambda=0.20$) for which it does affect the response.
- Putting emphasis on the effect of B on the maximum values of the aggravation factors behind the crest of canyons, one may observe that it does not practically affect the maximum $A_{h,top}$, whereas its decrease generally increases the maximum $A_{v,top}$. Focusing on the base of the canyons one may observe that the maximum $A_{h,top}$ reduces with reducing canyon width B.

TOPOGRAPHIC AGGRAVATION NEAR HILLS

As mentioned above, the topographic aggravation in the vicinity of slopes has already been parametrically studied by Bouckovalas & Papadimitriou (2005, 2006). Hence, the emphasis here was put on symmetric trapezoidal hills, that may be considered as a set of opposite facing identical slopes (of inclination i and normalized height H/λ) at a top distance with width B (see Fig. 2). Based on this figure, it is the finite value of the width B that differentiates the seismic response of symmetric hills from that of slopes, since the latter may be considered as hills with $B \to \infty$. In all analyses for hills, the topographic aggravation is estimated by dividing the 2D maximum horizontal a_h, and parasitic vertical, a_v, accelerations at all points on the ground surface with the maximum horizontal acceleration at the free field far from the hill $a_{h,base}$ (see Fig. 2) and thus defining $A_{h,base}$ and $A_{v,base}$. Similarly to what was performed for canyons, these topographic aggravation factors for hills with finite B may be directly compared to the pertinent factors for the slope having the same inclination i and normalized height H/λ, in order to study the effect of B on topographic aggravation.

Hence, Fig. 9 presents the variation of topographic aggravation factors $A_{h,base}$ and $A_{v,base}$ with horizontal distance from the left crest of hills with $i=30^o$, $H/\lambda=0.20$ and various widths B, namely B = 0.1H, H, 5H, 20H and $B\to \infty$. In parallel, Figure 10 shows the same comparison for hills with $i=30^o$, $H/\lambda=0.45$, in order to ascertain whether the conclusions from Figure 9 hold true for higher frequency motions. As for the cases of canyons, the seismic response of symmetric hills undergoing purely vertical impinging SV waves is also symmetric. Hence, these figures present the variation of topographic aggravation factors $A_{h,base}$ and $A_{v,base}$ by initiating plotting at a significant distance in front of the left slope of the hill and continuing until the axis of symmetry of the hill. As in the cases of canyons, in order to emphasize on the seismic response in the vicinity of the inclined slope of the hill (see shaded region), the horizontal distance is measured from the crest of the left slope of the hill (x=0) and results are plotted until x = –8H (= –400m), and do not extend as far as x = –20H that marks the end of the mesh. Note that based on the introduced normalization of peak accelerations, the $A_{h,base}$ at the free field in front of the toe of the hill is equal to 1.0, but for the top of the hill the 1D soil column response gives 7% (for $H/\lambda=0.20$) and 15% (for $H/\lambda=0.45$) lower peak horizontal acceleration, as denoted by the dashed line marked with $A_{h,base,ff} = a_{h,top}/a_{h,base}$ (see Figs 1 & 2, for definitions). It should be underlined here that the results for $B \to \infty$ presented in these figures are the same that were presented in the pertinent figures (i.e. Figs 3 & 4) for canyons. The difference in their numerical values comes about from the applied normalization, which for canyons was performed against the 1D free-field response behind the slope crest (see Fig. 1), while for hills against the 1D free-field response in front of the slope toe (see Fig. 2). This also explains the need for different notations of the topographic aggravation factors, i.e. $A_{h,top}$, $A_{v,top}$ for canyons and $A_{h,base}$, $A_{v,base}$ for hills. By observing Figs 9 & 10, the following conclusions may be drawn:

- The response for B=20H is practically identical to that of $B \to \infty$, meaning that a width of 20H is practically a large enough distance to disallow the wave interaction of the opposite facing slopes of the hill, irrespective of the wavelength λ of the vertically impinging SV waves.

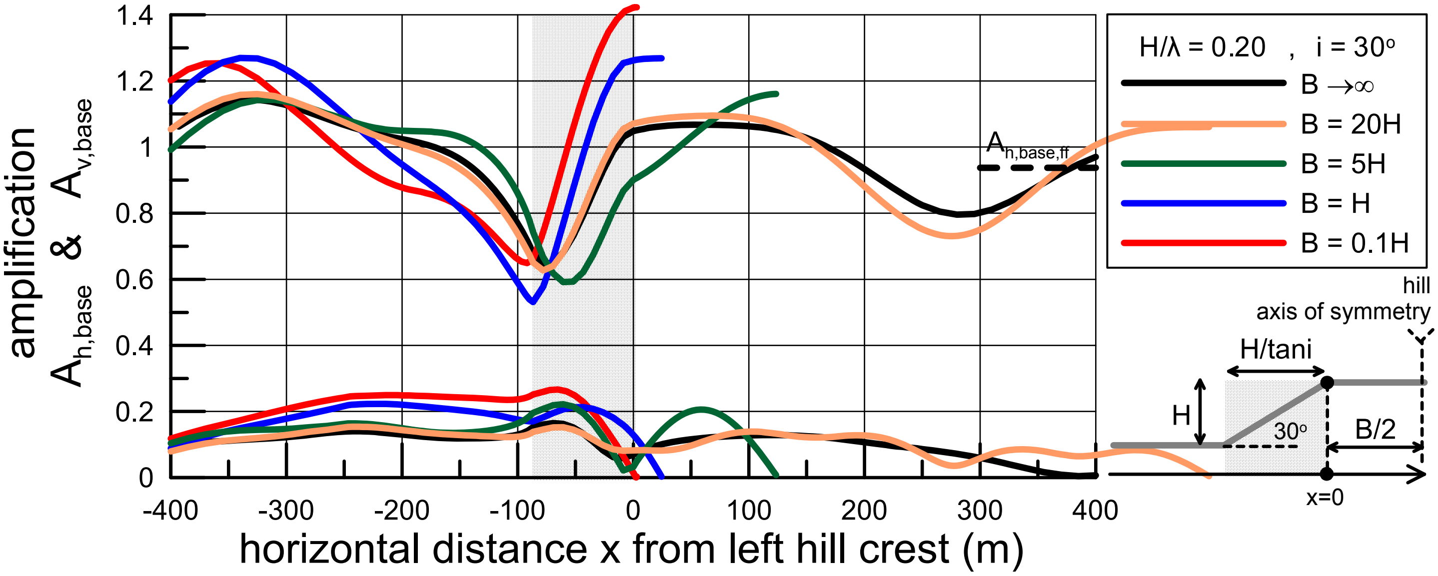

Fig. 9 Spatial variability of topographic aggravation factors $A_{h,base}$ and $A_{v,base}$ in the vicinity of symmetric trapezoidal hills with slope inclination $i=30^o$, normalized height $H/\lambda=0.20$ and various widths $B = 0.1H$, H, 5H, 20H and $B\rightarrow\infty$. Results are shown from x=-8H=-400m in front of the toe of the left slope and reach the axis of symmetry of the hill.

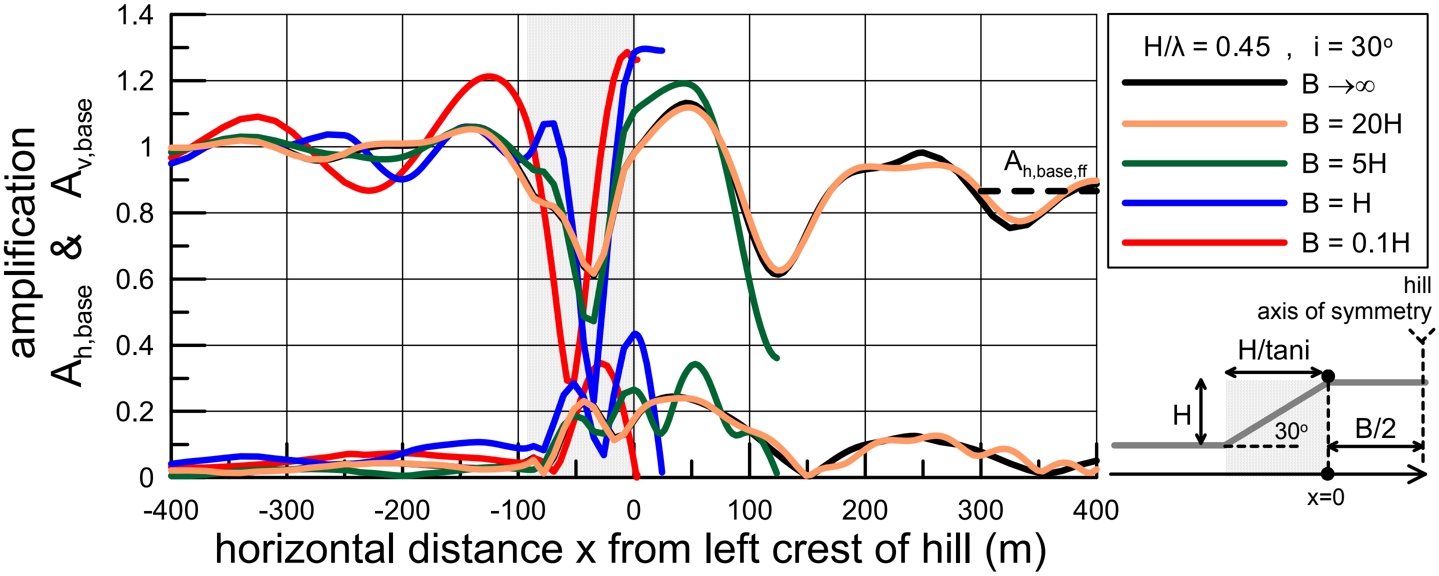

Fig. 10 Spatial variability of topographic aggravation factors $A_{h,base}$ and $A_{v,base}$ in the vicinity of symmetric trapezoidal hills with slope inclination $i=30^o$, normalized height $H/\lambda=0.45$ and various widths $B = 0.1H$, H, 5H, 20H and $B\rightarrow\infty$. Results are shown from x=-8H=-400m in front of the toe of the left slope and reach the axis of symmetry of the hill.

- In the area immediately behind the crest, horizontal motion is generally amplified, opposite to what is observed on the inclined slope (shaded area) that is characterized by deamplification, irrespective of the width B of the hill. Yet, at some distance from the toe of the hills, some horizontal amplification may be observed that is not significant and which dies out with distance, more rapidly for high frequency motions.
- Substantial parasitic vertical motions appear both in the area immediately behind the crest as well as on the inclined slope, irrespective of the width B of the hill. Yet, the parasitic vertical acceleration diminishes at the axis of symmetry of the hill.
- Width B affects significantly the topographic aggravation at the top of the hill, but less so the seismic motion in front of its toe.

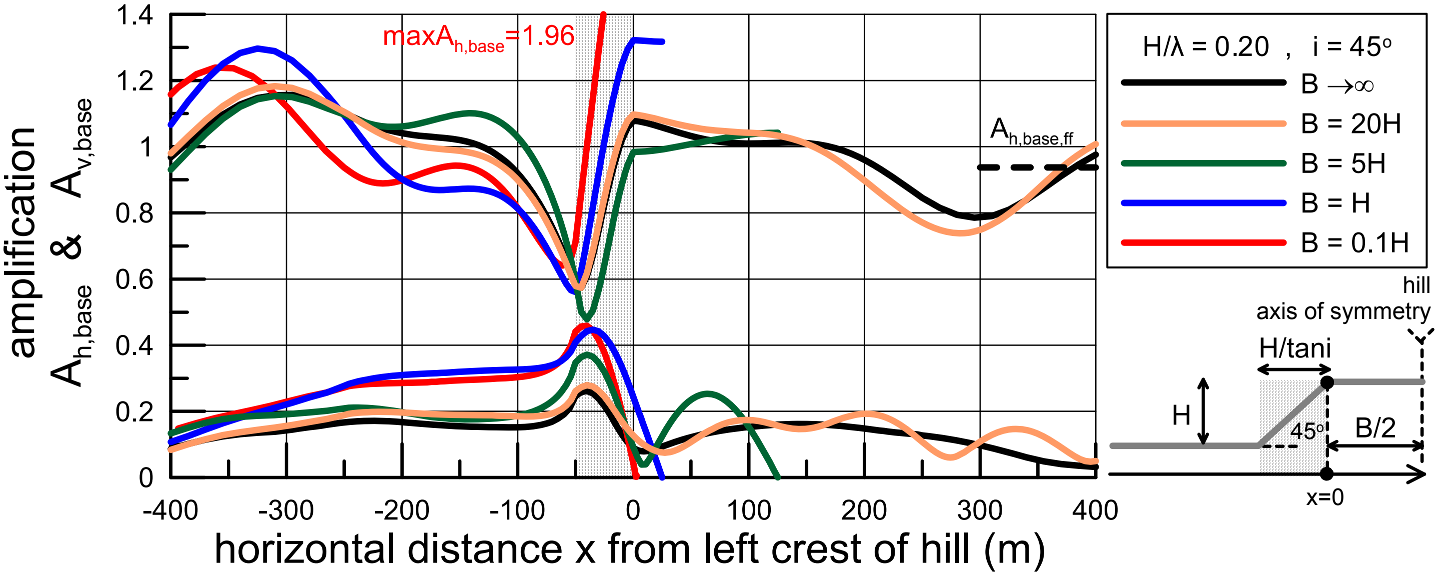

Fig. 11 Spatial variability of topographic aggravation factors $A_{h,base}$ and $A_{v,base}$ in the vicinity of symmetric trapezoidal hills with slope inclination i=45°, normalized height H/λ=0.20 and various widths B = 0.1H, H, 5H, 20H and B→∞. Results are shown from x=-8H=-400m in front of the toe of the left slope and reach the axis of symmetry of the hill.

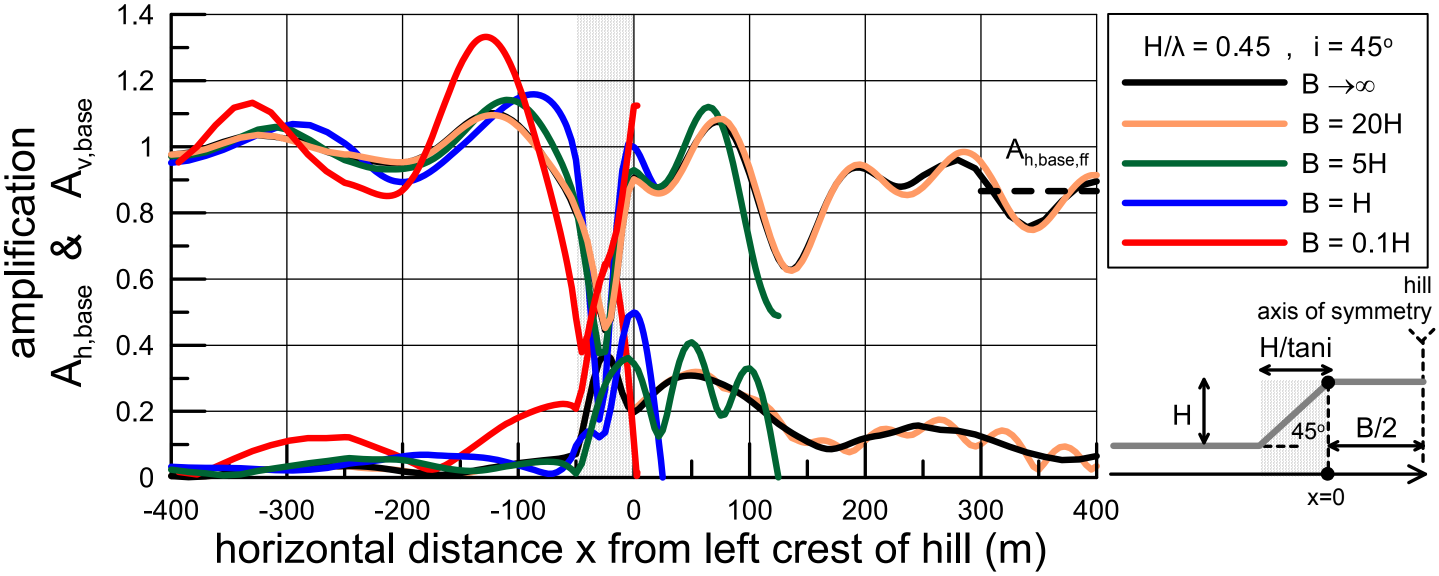

Fig. 12 Spatial variability of topographic aggravation factors $A_{h,base}$ and $A_{v,base}$ in the vicinity of symmetric trapezoidal hills with slope inclination i=45°, normalized height H/λ=0.45 and various widths B = 0.1H, H, 5H, 20H and B→∞. Results are shown from x=-8H=-400m in front of the toe of the left slope and reach the axis of symmetry of the hill.

In order to ascertain whether the foregoing conclusions are valid for hills with higher slope inclinations, Figs 11 and 12 present the respective results for hills with (i=45°, H/λ=0.20) and (i=45°, H/λ=0.45), while Figs 13 and 14 do the same for hills with (i=45°, H/λ=0.20) and (i=45°, H/λ=0.45). By observing these figures it may be deduced that the foregoing qualitative conclusions remain valid for higher slope inclinations. In addition, by critically reviewing all presented figures for the topographic aggravation in the vicinity of hills, the following may be observed:

- The slope inclination i increases the maximum horizontal amplification (i.e. maximum $A_{h,base}$) along the inclined slope and behind the crest of hills. Moreover, the smaller the width B of the hill the higher the value of the maximum $A_{h,base}$, which reaches its highest value equal to 3.54 for i=60° and H/λ=0.20. Similarly, the higher the λ of the impinging motion, the higher the maximum $A_{h,base}$, for the same top width B and slope inclination i, something that shows that it is the normalized width B/λ that governs this response, and not B or B/H.

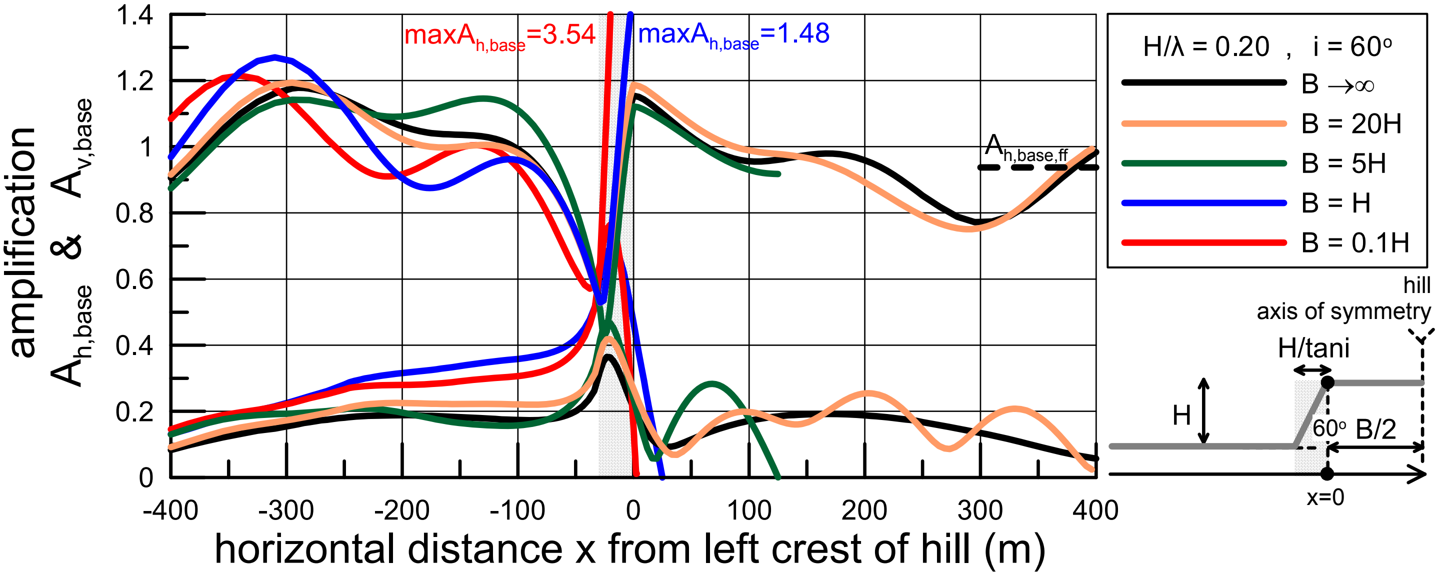

Fig. 13 Spatial variability of topographic aggravation factors $A_{h,base}$ and $A_{v,base}$ in the vicinity of symmetric trapezoidal hills with slope inclination i=60°, normalized height H/λ=0.20 and various widths B = 0.1H, H, 5H, 20H and B→∞. Results are shown from x=-8H=-400m in front of the toe of the left slope and reach the axis of symmetry of the hill.

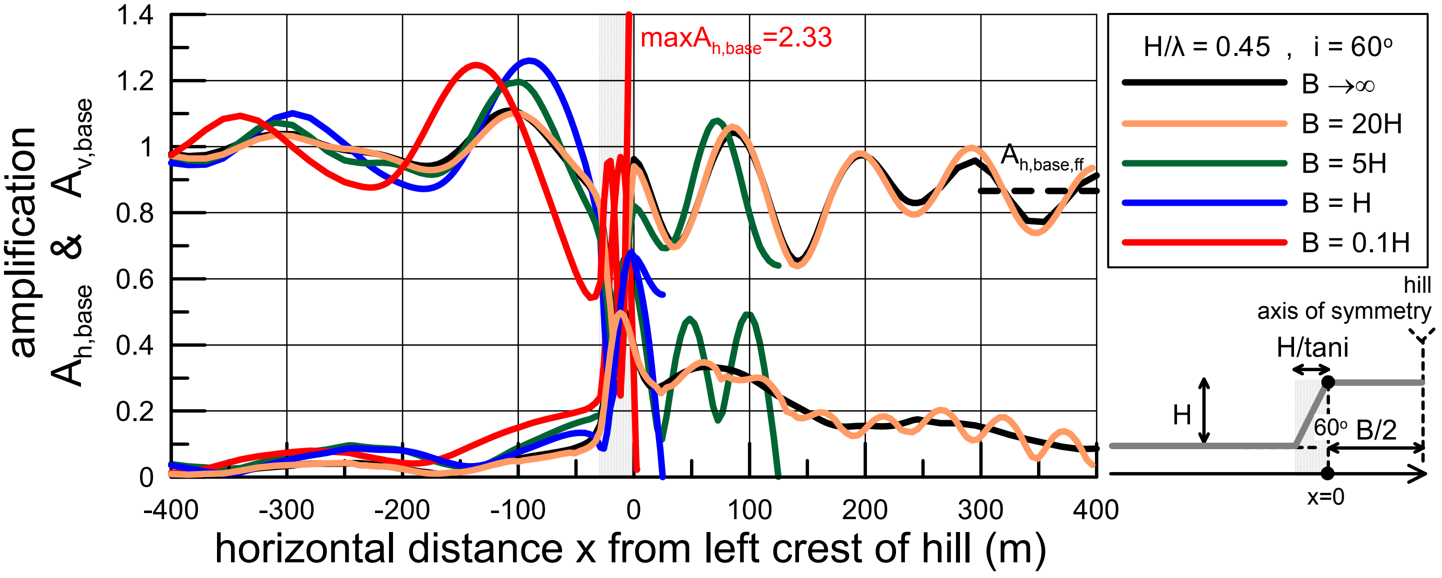

Fig. 14 Spatial variability of topographic aggravation factors $A_{h,base}$ and $A_{v,base}$ in the vicinity of symmetric trapezoidal hills with slope inclination i=60°, normalized height H/λ=0.45 and various widths B = 0.1H, H, 5H, 20H and B→∞. Results are shown from x=-8H=-400m in front of the toe of the left slope and reach the axis of symmetry of the hill.

- Similarly, the slope inclination i increases the maximum parasitic vertical amplification (i.e. maximum $A_{v,base}$) behind the crest of hills (but also along the inclined slope), something that is in agreement with similar results of Bouckovalas & Papadimitriou (2005, 2006) for slopes alone. Again, based on the same results for slopes, for smaller ($i < 30^o$) and larger ($i > 60^o$) slope inclinations, the maximum $A_{v,base}$ is similarly expected to reduce and increase respectively, something that has not been verified for slopes yet. Moreover, for high slope inclinations the parasitic vertical accelerations become comparable to their horizontal components, especially along the inclined slopes of hills (shaded regions).
- As for slopes and canyons, the spatial variability of the seismic aggravation on hills is more intense for high frequency motions, than it is for low frequency motions, and this is attributed to the horizontally travelling Rayleigh waves, as explained above.
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- Finally, based on all presented results, the effect of the width B on topographic aggravation is quite complex, since it does not monotonically affect the $A_{h,base}$ and $A_{v,base}$ factors. Unlike the topographic aggravation of canyons for which the effect of B seems important mostly for low frequency motions, for hills the effect of B is important for all impinging frequencies.
- Studying the effect of width B on the maximum values of the aggravation factors behind the crest of hills, one may observe the rapid increase of the maximum $A_{h,base}$ with reduced top width B. On the contrary, the maximum $A_{h,base}$ in front of the hill toe remains more or less independent of the hill top width B.

CONCLUSIONS AND DISCUSSION

This paper studies the topographic aggravation of 2D canyons, hills and slopes under vertically impinging harmonic SV waves. The study is performed numerically and in a parametric manner, by varying the slope inclination i, the normalized height H/λ and the width B of the topographic shapes. Focusing on the most important of the produced results, the following may be stated:

- Trapezoidal canyons produce lower or equal aggravations of the horizontal and vertical accelerations at their base, as compared to slopes with the same i and H/λ. In parallel, behind their crest, canyons show similar horizontal aggravations of the horizontal motion, but larger amplifications of the parasitic vertical accelerations, again compared to the respective slope.
- Trapezoidal hills produce much higher aggravation of the horizontal acceleration at their top, as compared to slopes with the same i and H/λ. In parallel, in front of their toe, hills show larger or equal aggravations of the horizontal and vertical acceleration, again compared to the respective slope.

Further analysis of the presented results is currently underway. Nevertheless, these results alone highlight the fundamental similarities and differences of the seismic response of different topographic shapes and may act as a guide for future analysis and interpretation. Closing, to avoid misconceptions, the limitations of the presented results should be outlined:

- The presented results pertain to 2D trapezoidal hills and canyons. In cases that the third dimension of the topographic shape is not practically infinite, then 3D analysis is unavoidable, since more intense amplifications may occur (e.g. in cases of 3D hills).
- For reasons of simplicity, the 2D topographic hills and canyons studied here were symmetric and the soil was assumed homogeneous. In cases that symmetry or soil homogeneity are not realistic assumptions, then case-specific analyses should be performed.
- In all analyses, material damping was set equal to 5%. This means that the results are pertinent to low intensity motions. In cases of strong excitations, material damping is expected to be higher, and all presented results in terms of topographic aggravation are expected to be less intense (e.g. Bouckovalas & Papadimitriou 2005). Hence, the presented topographic aggravation factors may be considered conservative, from an engineering point of view.
- The impinging motion consisted of harmonic SV waves, which experience larger amplifications as compared to similar SH or P waves (e.g. Ashford & Sitar 1997 for slopes, Geli et al 1988 for hills, Zhao & Valliappan 1993 for canyons) and therefore, all presented results are considered conservative, from an engineering point of view.
- The assumed incidence of the seismic excitation is vertical ($\beta = 0^o$). Yet, it has been demonstrated by many researchers (e.g. Wong 1982 for canyons, Geli et al 1988 for hills, Ashford & Sitar 1997 for slopes) that non-vertically incoming waves produce higher amplifications at the side of a symmetric topographic feature on which they impinge, as compared to the symmetric amplification pattern of vertically impinging waves ($\beta = 0^o$). Nevertheless, this angle of incidence β is practically unknown in engineering practice, and, in general, small angles of incidence are expected to appear for far field events, especially if soil stiffness reduces as it approaches the soil surface, i.e. for most cases in practice.

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