AGGRAVATION OF SPECTRAL ACCELERATION ALONG 2D SYMMETRICAL TRAPEZOIDAL VALLEYS

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ABSTRACT

This paper studies the effect of bedrock morphology on the aggravation of the elastic response spectrum at the surface of alluvial valleys. It focuses on 2D symmetrical valleys with trapezoidal (and triangular) cross section, having an aspect ratio B/H equal to 2, 4 and 20 (where B and H are the valley’s width and thickness, respectively) corresponding approximately to “narrow”, “usual” and “wide” valleys, respectively. The investigation is performed numerically by employing the finite difference method. The soil is considered homogeneous viscoelastic and is resting on a stiffer viscoelastic bedrock. The excitation consists of vertical impinging SV waves in the form of time histories based on actual earthquake recordings. This study shows that “narrow” valleys may give excessive aggravations at their central area and for low structural periods, while “usual” valleys may also give significant amplifications near their center, especially for structural periods near the resonance period of the valley. On the other side, “wide” valleys condition their geomorphic aggravation on the characteristics of the applied excitation, but the amplification is expected mainly at the edges of the valley and for structural periods near the predominant excitation period.

Keywords: basin effects; numerical analysis; spectral acceleration; valley effects; seismic aggravation

1. INTRODUCTION

Accurate estimation of the seismic loading per location is crucial for the safe design of structures. Existing seismic codes provide design spectra for different ground categories (e.g., EC8 for 5 ground categories), but the ground category selection is based on the first few meters of the soil profile (e.g., 30m in EC8), without considering whether the location is on a slope, or within a valley. As such, topographic or valley effects on seismic ground motion are not explicitly taken into account in the design of structures. However, there are numerous earthquakes worldwide (e.g., Armenia 1988, Loma Prieta 1989, L’Aquila 2009) where the earthquake recordings illustrate and/or structural damage patterns imply that the ground motion varies considerably at different locations within valleys, and this variability is not expected based on the local soil conditions.

The majority of the relevant literature studies are nowadays numerical (in the past they were analytical) and are either of a parametric nature (e.g., Gelagoti et al. 2010; Papadimitriou et al. 2011), or are aimed at the simulation of case histories. In all cases, the basic mechanisms of response identified in early studies are repeatedly observed. For example, Bard and Bouchon (1980) studied the response of two differently-shaped alluvial valleys and concluded that local aggravation of seismic motion at the ground surface is due to surface waves (Love waves when the SH waves are incident; Rayleigh waves in the case of SV and P waves) generated at the valley boundaries. In addition, the large majority of the studies focus on the aggravation of the peak intensity at the ground surface (e.g. peak ground acceleration) and few highlight the alteration of the frequency content of the motion (e.g. Havenith et al., 2009; Vessia et

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In quantitative terms, the amount of aggravation at each location is governed by the exact valley geometry (2D, 3D, etc.), the type of incident waves (SH, SV, P), the incident wave angle (different from vertical), the (predominant) period of the bedrock excitation, as well as the soil and bedrock properties (e.g., Sanchez-Sesma et al., 1988; Loukakis and Bielak, 1995). The multitude of these important problem parameters explains why valley effects on ground motion are still not included in seismic codes and underlines the need for further systematic study. Trying to remedy this shortcoming, the relatively recent works of Vessia et al. (2011), Gatmiri et al. (2012, 2014) and Riga et al. (2016) propose relations for approximately estimating valley effects.

In this paper, a numerical study is presented, in which a number of these important problem parameters are considered fixed (e.g., soil and bedrock properties, incident wave type and angle) and the emphasis is set on the study of the effects of the valley shape and the (predominant) period of the bedrock excitation. Particularly, 2D symmetrical trapezoidal valleys with a horizontal ground topography (as illustrated in Fig. 1) with different values of the aspect ratio B/H (where B and H are the valley’s width and thickness) were considered herein. These valleys were excited with vertically impinging SV waves with time histories originating from actual seismic recordings that had widely different predominant periods. Unlike most studies in the literature, this paper focuses on the aggravation of the whole of the elastic response spectrum, and not only of the peak ground acceleration. Section 2 of the paper outlines the employed numerical methodology and provides the definitions of the aggravation factors that quantify valley effects. Then, section 3 outlines the performed analyses for valleys with different aspect ratios under exemplary high frequency and low frequency motions, whose results are presented in section 4. The paper ends with conclusions outlining the basic findings of this numerical effort.

![Illustration of 2D symmetric trapezoidal valley: definitions of parameters, analyzed domain and boundary conditions.](image)

**Figure 1.** Illustration of 2D symmetric trapezoidal valley: definitions of parameters, analyzed domain and boundary conditions.

## 2. NUMERICAL METHODOLOGY

For the analyses presented herein, the finite difference method was employed via FLAC v7.0 (Itasca Consulting Group Inc. 2011). Plane strain analyses were performed for two-dimensional (2D) symmetrical trapezoidal alluvial valleys. As illustrated in Figure 1, these valleys had width B (at the ground surface), thickness H (from the horizontal ground surface at the valley center) and bedrock slope inclination i (at the valley edges). The analysis domain was quite wider than the studied valley, since the discretized homogenous bedrock extended to a depth of 450m below the horizontal soil-bedrock interface and laterally to 500m from either side of the alluvial valley. Hence, the total width and thickness of the mesh in each analysis was a function of B, H and i. This wide and deep discretization
of the bedrock aimed at minimizing the effects of artificial reflections (at the mesh boundaries) on the seismic response within the valley. For the same reason, free field boundaries were set at the lateral boundaries and quiet (horizontal and vertical) boundaries were assigned at the bottom of the mesh. In all analyses, the excitation was applied as a time-history of shear stress at the bottom horizontal boundary of the mesh, thus applying vertically incident SV waves to the domain. Selecting to apply the excitation as a time-history of stress, rather than displacement (velocity or acceleration) allows in concept free vibration of the bottom boundary, thus disallowing artificial reflections in combination with the assigned quiet boundaries.

Overall, the mesh was denser in the area of the alluvial valley, where the vertical thickness of zones was equal to 5m. This zone thickness is quite small, even for the case of the minimum predominant S wavelength of the performed analyses $\lambda_{\text{min}} = 90$ m, since this zone thickness is equal to $\lambda_{\text{min}}/18$, a value small enough not to affect the travelling waves within the valley. In all cases, the soil and the bedrock were considered uniform viscoelastic materials (for simplicity), with the same density $\rho = 2$ Mg/m$^3$ and elastic Poisson’s ratio $\nu = 1/3$ (for simplicity), but different shear wave velocities, denoted as $V_s$ for the soil and $V_b$ for the rock. The actual, frequency-independent, hysteretic damping of a geomaterial is simulated with the use of Rayleigh damping which is frequency-dependent. As in all commercial codes, combined (mass and stiffness) Rayleigh damping assigns a minimum value of damping $\xi_{\text{min}}$, to a desired target frequency $f_{\text{ref}}$ and larger values of damping to frequencies larger and smaller than $f_{\text{ref}}$, namely up to 20% higher damping for frequencies 50% lower and 100% higher than $f_{\text{ref}}$. Hence, not only the $\xi_{\text{min}}$ required calibration, but also the $f_{\text{ref}}$ had to be calibrated within the frequency range of interest in each analysis. The frequency range of interest herein lies between the predominant frequency of the (bedrock) excitation $f_s$ and the fundamental frequency of the soil layer $T_s$, assuming 1D seismic response. Hence, the $f_{\text{ref}}$ was always set equal to the average value of $f_s$ and $f_s$ that were different in each analysis.

The emphasis in this study is the so-called geomorphic aggravation of seismic ground motion, i.e. the aggravation that is due purely to the existence of a non-horizontal soil-bedrock interface (valley effects) and the aggravation that is due to the soil layer (soil effects) as opposed to having only bedrock to ground surface. This de-coupling of the two effects cannot be performed one the basis of a 2D analysis of a valley domain (in the form of Figure 1), since the observed variability of ground motion within the valley is a combined effect of both the soil and the valley. In order to isolate valley effects, for each 2D valley analysis (denoted as 2D_valley) a couple of 1D seismic ground analyses were also performed (with FLAC v7.0) for the same excitation and damping configuration. One analysis (denoted as 1D_soil) considered the soil layer of infinite width and provided its 1D (free-field) soil amplification and a second analysis (denoted as 1D_rock) considered the 1D (free-field) bedrock amplification of the motion.

Geomorphic aggravation of seismic ground motion is defined in terms of the spectral acceleration $S_a$ for 1-DOF structures with different fundamental periods $T$ and structural damping 5% of critical. Particularly, from each 2D_valley analysis, the elastic response spectrum for the horizontal acceleration $S_{a_h}^{2D}$ and the parasitic vertical acceleration $S_{a_v}^{2D}$ for all locations of the ground surface were retrieved. The term “parasitic” is introduced for the $S_{a_v}^{2D}$, since the incident motion concerns purely horizontal vibration (vertically incident SV waves) and therefore any vertical vibration at the ground surface is a result of valley effects. Then, from the corresponding 1D_soil and 1D_rock analyses, the values of $S_{a_h}^{1D_{\text{soil}}}$ and $S_{a_h}^{1D_{\text{rock}}}$ were retrieved, i.e. the respective values of the elastic response spectrum for the horizontal acceleration. Obviously, the respective values of $S_{a_h}^{1D_{\text{soil}}}$ and $S_{a_h}^{1D_{\text{rock}}}$ are equal to zero for 1D shaking conditions, as those in the 2 respective analyses. For the quantification of geomorphic aggravation on the elastic response spectrum, two dimensionless spectral ratios of geomorphic aggravation $(AS_{a_h}, AS_{a_v})$ are adopted. These ratios are functions of the location along the valley and the structural period $T$ (for damping $\xi=5\%$ of critical). The $AS_{a_h}$ ratio is defined as the ratio of the elastic response spectrum for the horizontal acceleration $S_{a_h}^{2D}$ at each location over the elastic response spectrum in the horizontal direction corresponding to 1D shaking at the same location. Hence, for locations along the valley, the denominator of $AS_{a_h}$ is equal to $S_{a_h}^{1D_{\text{soil}}}$, whereas along the outcropping bedrock the denominator is equal to $S_{a_h}^{1D_{\text{rock}}}$, as illustrated in Figure 2. Similarly, the numerator of $AS_{a_v}$ is the elastic response spectrum of the parasitic vertical acceleration $S_{a_v}^{2D}$ at each location, while the denominator is the same as for the $AS_{a_h}$ ratio, i.e. it is different along the valley and along the
outcropping bedrock (Figure 2). In terms of notation, the location along the ground surface is depicted via its distance $x$ from the axis of symmetry (center) of the valley, after its normalization of the valley width $B$. Positive values of $x/B$ denote the right segment of the valley, while negative values its left segment, with the values of $x/B = 0.5$ and $-0.5$ depicting its right and left edges respectively.

![Figure 2. Definition of horizontal (AS$_{h}$) and parasitic vertical (AS$_{v}$) spectral geomorphic aggravation at different locations along the valley.](image)

3. OUTLINE OF ANALYSES

As discussed in the introduction, this problem is characterized by a number of parameters dealing with 2D valley geometry ($B$, $H$, $i$), soil conditions ($\rho_s$, $V_s$, $\rho_b$, $V_b$, $\xi_{min}$) and excitation characteristics (intensity, frequency content, type of waveform, angle of incidence). Regarding the 2D valley geometry, the literature agrees that one of the most important factors in geomorphic aggravation is the aspect ratio ($B/H$) of the valley (e.g. Bard and Bouchon 1985; Papadimitriou et al. 2011). For this purpose, 3 valley geometries are investigated in this paper covering a wide range of probable geometries. In particular, as shown in Figure 3 and Table 1, these 3 geometries correspond to a “narrow” (triangular) valley ($B/H=2$), a “usual” valley ($B/H=4$) and a “wide” valley ($B/H=20$). Their shape is presented in Figure 3, while their characteristics are summarized in Table 1 (note $\xi_{min}=5\%$ corresponds to the minimum value of the combined mass and stiffness Rayleigh damping for the valley geomaterials).

![Figure 3. Cross sections of analyzed 2D valleys: B/H=2 “narrow”, B/H=4 “usual”, B/H=20 “wide”](image)
Table 1. Geometric, geotechnical and vibration characteristics of analyzed 2D valleys.

<table>
<thead>
<tr>
<th>B/H</th>
<th>B (m)</th>
<th>H (m)</th>
<th>V_s (m/s)</th>
<th>V_b (m/s)</th>
<th>i (°)</th>
<th>ξ_min (%)</th>
<th>α</th>
<th>T_r (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>200</td>
<td>50</td>
<td>500</td>
<td>1000</td>
<td>45</td>
<td>5</td>
<td>0.5</td>
<td>0.23</td>
</tr>
<tr>
<td>2</td>
<td>400</td>
<td>200</td>
<td>500</td>
<td>1000</td>
<td>45</td>
<td>5</td>
<td>0.5</td>
<td>0.52</td>
</tr>
<tr>
<td>20</td>
<td>1000</td>
<td>50</td>
<td>500</td>
<td>1000</td>
<td>45</td>
<td>5</td>
<td>0.5</td>
<td>0.39</td>
</tr>
</tbody>
</table>

Note in Table 1 the term $T_r$, which corresponds to the resonance period of the valley under SV incoming waves and is given by Eq. (1) on the basis of Bard and Bouchon (1985):

$$T_r = \frac{T_s}{\sqrt{1+\left(\frac{5.8H}{B}\right)^2}}$$

where $T_s = 4H/V_s$ is the fundamental soil period under 1D shaking. Note in Table 1 and Figure 3 that the 3 valleys have the same bedrock angle $i$ and the same $V_s$ and $V_b$ values. This selection is based on the literature finding that the effects of the bedrock angle $i$ and the impedance ratio $\alpha = \rho_s V_s/\rho_b V_b$ prove of secondary importance for geomorphic amplification (Papadimitriou et al., 2011). Hence, the examined symmetrical and trapezoidal valleys in this work have relatively steep boundaries ($i = 45°$) and soil that is quite softer than the underlying bedrock ($\alpha = 0.5$). Particularly, given the uniform value of density, this value of $\alpha = 0.5$ is materialized via $V_s = 500\text{m/s}$ and $V_b = 1000\text{m/s}$, corresponding to stiff soil conditions over hard bedrock (Ground Category A according to EC8).

Regarding the excitation characteristics, in all analyses the type of waveform and the angle of incidence are kept constant, since vertically impinging SV waves are considered. Given the use of visco-elastic analyses, the intensity of the excitation does not affect the results in terms of aggravation factors ($\text{ASa}_h$ and $\text{ASa}_v$), since soil stiffness ($V_s$ values) and damping $\xi_{\text{min}}$ remain constant. Hence, in such analyses the effects of intensity of the excitation may be indirectly introduced via an explicit change in soil parameters (e.g. an increase of $\xi_{\text{min}}$ for high-intensity motions). This was not considered here, where the $\xi_{\text{min}}$ of (combined mass and stiffness Rayleigh) damping is considered equal to 5% for all analyses, a value reflecting low and medium intensity excitations, for which geomorphic aggravation is expected to be spatially significant along the valley, unlike high intensity excitations were the phenomenon is relatively damped out spatially (Gelagoti et al. 2010).

Figure 4. Normalized elastic response spectra (for 5% structural damping) of the high-frequency excitation (Kefalonia 1983) and the low-frequency excitation (Coyote Lake 1979) used as base motions, in comparison to normalized EC8 design spectrum for Ground Category A (high seismicity areas with magnitude M > 5.5)
4. EFFECT OF IMPORTANT PROBLEM PARAMETERS

Figures 5 through 10 present the results of the performed seismic ground response analyses. These are used for studying the effects of important problem parameters on the geomorphic aggravation of seismic ground motion. Particularly, Figure 5a (top plot) presents the spatial variation of the geomorphic aggravation factor $AS_a_h$ (for the horizontal spectral acceleration) along the surface of the “narrow” (triangular) valley with $B/H = 2$, when it is excited by a high-frequency excitation (namely the Kefalonia recording). The horizontal distance $x$ is measured from the axis of symmetry of the valley and it is presented after normalization against the valley width $B$. Hence, locations with $|x/B| < 0.5$ are within the valley, whereas locations with $|x/B| > 0.5$ are along the outcropping bedrock. Differently colored solid curves present the results for different structural periods, from $T=0$ (peak ground acceleration) up to $T = 2$ sec. The cyan dashed line depicts the peak spectral acceleration per location, regardless of the structural period $T$ for which it is expected. Figure 5b (bottom plot) adopts the same format for presenting the results for the spatial variation of the geomorphic aggravation factor $AS_a_v$ (for the parasitic vertical spectral acceleration) along the same (“narrow”) valley, under the same (Kefalonia) excitation and for the same values of structural period $T$. Then, Figure 6 (in the same dual plot format) presents the respective results for geomorphic aggravation of seismic ground motion for the same (“narrow”) valley, but under the low-frequency excitation (namely the Coyote Lake recording). As a duet, Figures 5 and 6 provide insight into the effect of frequency content on geomorphic aggravation of seismic ground motion for “narrow” valleys ($B/H = 2$). Similarly, Figures 7 and 8 present the respective results for “wide” valleys ($B/H = 20$), whereas Figures 9 and 10 do the same for “usual” valleys with intermediate $B/H$ values ($B/H = 4$ here). As a whole, Figures 5 through 10 provide the basis for studying the effects of valley aspect ratio $B/H$, (predominant) excitation period $T_e$ and structural period $T$ on geomorphic aggravation of spectral acceleration, as presented in sections 4.1, 4.2 and 4.3, respectively.

4.1 Effect of valley aspect ratio $B/H$

The effect of valley aspect ratio $B/H$ is studied by comparing results for valleys with different aspect ratios $B/H$ (equal to 2, 4 and 20) under the same excitation. Hence, based on Figures 5 and 6 it is deduced that (very) “narrow” (triangular) valleys ($B/H = 2$) give excessive aggravations (e.g., $AS_a_h$ up to 2.2 and $AS_a_v$ up to 1.2). On the other hand, on the basis of Figures 7 and 8, it is concluded that for (very) “wide” valleys ($B/H = 20$), the aggravation becomes much smaller, since the $AS_a_h$ values have a maximum of 1.5, whereas the $AS_a_v$ values are smaller than 0.55. This means that the valley is relatively too thin to affect considerably the incoming wave. As expected, for “usual” valleys ($B/H = 4$), geomorphic aggravation is significant (see Figures 9 and 10), since the $AS_a_h$ and $AS_a_v$ values reach a maximum of 2.0 and 0.8 respectively, i.e. the maxima are higher than for $B/H = 20$ and lower than for $B/H = 2$.

Regarding the spatial variability of geomorphic aggravation, it is deduced that for “wide” valleys the peak horizontal aggravation is observed near the boundaries of the valley, regardless of the structural period $T$ (see Figures 7 and 8). On the contrary, for “usual” and “narrow” valleys ($B/H = 4, 2$) the peak horizontal aggravation is observed at the valley center. This shift for the location of the peak horizontal aggravation for “wide” valleys is because the generated surface waves are damped out on their way to the center of the valley. Hence, approximately 1D seismic response is expected at the center of the “wide” valleys, but the aggravation due to seismic wave reflections at the inclined boundaries remains unaffected. However, for “narrow” valleys, the generated surface waves affect the center of the valley practically concurrently with the incident vertical waves, thus locating the area of peak horizontal aggravation at the center of the valley. The shift of the area of peak horizontal aggravation towards the boundaries of valleys occurs gradually with an increase of the valley aspect ratio $B/H$.

For the parasitic vertical aggravation, in all cases, there is $AS_a_v = 0$ observed at $x/B = 0$, due to the symmetry of the problem (symmetrical valley under vertically impinging waves). The location of peak parasitic vertical aggravation is therefore never at $x/B = 0$, and it is usually located at values of $|x/B|$ higher than 0.1. As the valley aspect ratio $B/H$ increases, a trend for shifting this location towards the valley boundaries is observed, which is very pronounced for “wide” valleys for which this location is the same for all structural periods $T$. 

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Figure 5. Spatial variation of spectral geomorphic aggravation of horizontal $\text{AS}_{a_h}$ and parasitic vertical $\text{AS}_{a_v}$ acceleration for different structural periods $T$, along “narrow” valleys ($B/H=2$) under a high-frequency excitation.

Figure 6. Spatial variation of spectral geomorphic aggravation of horizontal $\text{AS}_{a_h}$ and parasitic vertical $\text{AS}_{a_v}$ acceleration for different structural periods $T$, along “narrow” valleys ($B/H=2$) under a low-frequency excitation.
Figure 7. Spatial variation of spectral geomorphic aggravation of horizontal $A_{Sa_h}$ and parasitic vertical $A_{Sa_v}$ acceleration for different structural periods $T$, along “wide” valleys ($B/H=20$) under a high-frequency excitation.

Figure 8. Spatial variation of spectral geomorphic aggravation of horizontal $A_{Sa_h}$ and parasitic vertical $A_{Sa_v}$ acceleration for different structural periods $T$, along “wide” valleys ($B/H=20$) under a low-frequency excitation.
Figure 9. Spatial variation of spectral geomorphic aggravation of horizontal $\text{ASA}_h$ and parasitic vertical $\text{ASA}_v$ acceleration for different structural periods $T$, along “usual” valleys ($B/H=4$) under a high-frequency excitation.

Figure 10. Spatial variation of spectral geomorphic aggravation of horizontal $\text{ASA}_h$ and parasitic vertical $\text{ASA}_v$ acceleration for different structural periods $T$, along “usual” valleys ($B/H=4$) under a low-frequency excitation.
4.2 Effect of (predominant) excitation period

The effect of predominant excitation period $T_e$ is studied by comparing results for the same valley under different excitations, i.e., a high-frequency one (Kefalonia with $T_e = 0.18$sec) and a low-frequency one (Coyote Lake with $T_e = 0.42$sec). Hence, focusing on “narrow” valleys, Figures 5 and 6 show that the peak horizontal aggravations are expected at the valley center regardless of the applied excitation. However, a high-frequency excitation (in Figure 5) gives higher amplifications in comparison to low-frequency excitations (Figure 6) and this in both components of motions. Particularly, the maximum $\text{ASA}_h$ and $\text{ASA}_v$ values of 2.2 and 1.2 for the high-frequency excitation reduce to 1.9 and 0.8 for the low-frequency one. In any case, the geomorphic aggravations are quite significant for any excitation period, due to the “narrow” geometry of the valley.

As shown in Figures 9 and 10, for “usual” valleys ($B/H = 4$) the peak aggravations are expected at the valley center regardless of the applied excitation, i.e. similarly to what is observed for “narrow” valleys ($B/H = 2$). Additionally, high-frequency excitations give comparatively higher values of aggravation (e.g., $\text{ASA}_h$ and $\text{ASA}_v$ values up to 2 and 0.8, respectively for the high-frequency excitation in Figure 9, versus values up to 1.3 and 0.4 for the low-frequency excitation in Figure 10).

On the contrary, “wide” valleys ($B/H = 20$) condition their geomorphic aggravation on the characteristics of the applied excitation. Observe in Figure 8 that the geomorphic aggravation is insignificant (e.g., $\text{ASA}_h < 1.2, \text{ASA}_v < 0.3$) and the seismic response is practically 1D, whereas in Figure 7 considerable aggravations are observed (e.g., $\text{ASA}_h$ up to 1.5 and $\text{ASA}_v$ up to 0.8), mainly at the edges of the valley. This great difference in the response is solely due to the excitation period, since both these figures refer to the same “wide” valley. Of interest is also a comparison of the excitation period with the fundamental soil period under 1D shaking, $T_s$, that has a value of 0.4sec for $H = 50m$ and $V_s = 500m/s$. This implies that for “wide” valleys, an essentially 1D response is expected for low-frequency excitations and especially when the predominant excitation period $T_e$ is greater or equal to $T_s$, an unlikely event for thick valleys. On the contrary, considerable aggravations are expected (at the valley edges) when the fundamental soil period $T_s$ is larger than $T_e$, a quite common case for alluvial valleys.

4.3 Effect of structural period $T$

The effect of structural period $T$ is studied by comparing differently colored curves in each plot of Figures 5 through 10. A common general conclusion is that the intensity of geomorphic aggravation is not the same for all structural periods $T$, i.e. geomorphic aggravation does not affect uniformly the elastic response spectrum. However, qualitatively the spatial variability of geomorphic aggravation is more or less independent of structural period $T$, e.g., the aggravation becomes maximum at the same locations along the valley regardless of the value of $T$, and this holds true for all values of $B/H$. Note also that the peak aggravation does not appear for any specific structural period $T$. However, the aggravation of the peak ground acceleration (i.e. for $T = 0$; black curves in Figures 5 through 10) is characteristic of the overall aggravation, since it shows whether this is intense or not. Additionally, the locations where the aggravation for $T = 0$ becomes maximum coincide with the locations where the maximum aggravation (dashed blue curves) becomes maximum. The above observations hold true for all values of the valley aspect ratio $B/H$.

At any valley, geomorphic aggravations become essentially negligible for structural periods $T$ greater than 1D fundamental soil period $T_s$. For example, while the geomorphic aggravation is very intense for the “narrow” valley with $B/H = 2$, the aggravations are very small ($\text{ASA}_h < 1.1, \text{ASA}_v < 0.25$) for $T = 2$sec which is greater than the $T_s = 1.6$sec (see Figures 5 and 6). Similarly for the “usual” and “wide” valleys with $B/H = 4$ and 20, geomorphologic aggravation is very small ($\text{ASA}_h < 1.1, \text{ASA}_v < 0.20$) for values of $T ≥ 0.5$sec, that are all greater than the $T_s = 0.4$sec (see Figures 7 through 10). Interestingly, for “usual” valleys ($B/H = 4$), the peak aggravations are observed for periods $T$ near the valley resonance period $T$, that are shown in Table 1, on the basis of Bard and Bouchon (1985). Observe in Figures 9 and 10 that the results for $T = 0.22$sec are near the maximum aggravations for both excitations (note that $T_e = 0.23$sec in Table 1). For the “narrow” valley ($B/H = 2$), the aggravations seem significant for structural
period $T$ up to the value of $T_r$ and seem to decrease thereafter. Note in Figures 5 and 6, that the $\text{AS}_{a_h}$ and $\text{AS}_{a_v}$ values are significant for $T = 0, 0.1, 0.22$ and $0.50$ sec, i.e. for periods smaller or equal to $T_r = 0.52$ sec (see Table 1). Finally, for the “wide” valley, the $T_r$ seems to play less of a role, since relatively significant aggravations are expected for periods up to the range of the predominant period $T_e$, i.e. for $T = 0, 0.1$ and $0.22$ sec when $T_e = 0.18$ sec (Figure 7) and for $T = 0, 0.1, 0.22$ and $0.50$ sec when $T_e = 0.42$ sec (Figure 8).

4.4 Comparison with literature findings

Direct comparison of the results presented in Figures 5 through 10 with the literature that provides guidelines for estimating geomorphic aggravation is not always easy. The reason is that different studies are based on differently shaped valleys, while they employ different indices of geomorphic aggravation. For example, Gatmiri and Foroutan (2012) and Gatmiri and Amini-baneh (2014) provide a methodology for estimating the Spectral Ratio, i.e. the peak 2D spectral aggravation (regardless of structural period $T$) at different locations along the valley, with respect to the outcropping bedrock (and not the 1D soil) response. Of the reviewed literature, only the study of Vessia et al. (2011) provides estimates of geomorphic aggravation that are directly comparable with our analyses. As an example, Figure 11 compares the numerical results of $\text{AS}_{a_h}$ at locations along the valley with different normalized distance from the center ($x/B$), with the pertinent design proposals of Vessia et al. (2011) for the case of “usual” valleys ($B/H=4$) and the high-frequency (Kefalonia) excitation.

![Figure 11. Spectral geomorphic aggravation of horizontal $\text{AS}_{a_h}$ acceleration, at different locations ($x/B$) along “usual” valleys ($B/H=4$) under a low-frequency excitation, and comparison with Vessia et al. (2011).](image)

This figure shows that basic aspects of the predicted response are in tune with literature. For example, note that the central area ($x/B=0$) suffers from the highest aggravation for this valley-excitation combination, and that geomorphic aggravation is negligible at high structural periods $T$ for all locations. However, the same valley under a low-frequency excitation has much lower aggravations (compare results in Figures 9 and 10) and this is not considered in the proposal of Vessia et al. (2011), which also does not provide similar estimates for $\text{AS}_{a_v}$.

5. CONCLUSIONS

This paper presents results from a numerical investigation of geomorphic aggravation on the elastic response spectrum for the horizontal and the parasitic vertical acceleration. The analyses, and the thereby derived conclusions, pertain to 2D symmetric trapezoidal valleys with uniform soil and rock conditions under vertically incident SV waves. Specifically, the basic conclusions drawn from this work are:

- The most important problem parameter for determining geomorphic aggravation is the valley aspect ratio $B/H$, where $B$ is the width of valley and $H$ is its thickness. Other important parameters are the predominant excitation period $T_e$ (for all valleys) and the valley resonance period $T_r$ (for valleys with relatively small values of $B/H$).
• As the valley aspect ratio B/H reduces, geomorphic aggravation increases. However, for any given B/H value, high-frequency excitations produce comparatively more intense geomorphic aggravation than low-frequency motions.
• «Narrow» valleys (e.g. B/H = 2) may give excessive aggravations (e.g. AS_{h} > 2.2 and AS_{r} up to 1.2) at their central area and for structural periods T smaller or equal to the resonance period T_{r} of the valley. Similarly, «usual» valleys (e.g. B/H = 4) may give significant aggravations (e.g. AS_{h} up to 2.0 and AS_{r} up to 0.8) near their center, and these aggravations become very intense for structural periods T near the resonance period T_{r} of the valley.
• «Wide» valleys condition their geomorphic aggravation on the characteristics of the applied excitation. In particular, in the unusual cases that the predominant excitation period T_{p} is greater than the 1D fundamental soil period T_{s}, the aggravation is insignificant (e.g. AS_{h} < 1.1, AS_{r} < 0.3). However, in the more usual cases that that T_{p} ≥ T_{s}, considerable aggravations (AS_{h} up to 1.4 and AS_{r} up to 0.5) are expected, mainly at the edges of the valley and for structural periods T near the predominant excitation period T_{p}.
• At any valley, geomorphic aggravation becomes insignificant for structural periods T greater than the 1D fundamental soil period T_{s}.

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7. REFERENCES


