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Two-dimensional site effects on the seismic response of alluvial valleys: the case study of the Aterno river valley (Italy)

Effets de site bidimensionnels sur la réponse sismique des vallées alluviales: étude de cas de la vallée de la rivière Aterno (Italie)

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ABSTRACT: The seismic response of an alluvial valley is mainly ruled by a combination of geometrical (e.g. shape ratio and inclination of the edges) and stratigraphical factors (e.g. shear wave velocity profile and non-linear soil behaviour). Usually, the influence of these parameters on the amplification of seismic motion is studied carrying out complex and time-consuming non-linear 2D or 3D numerical analyses. In fact, it has not yet been adequately studied if it is possible to decouple the two effects and how to study them separately. In this study, a set of 1D and 2D numerical analyses was carried out to investigate the influence of non-linearity on the seismic response of alluvial valleys and try to isolate this effect from that of the other parameters. A cross-section along the Aterno valley (L'Aquila - Italy) was considered to build the 2D model of a simplified trapezoidal valley. The results of 2D numerical analyses have been compared to the 1D response along the profile at the center of the valley, in terms of ratio between spectral amplification factors, to quantify the influence of geometry on the response of the valley. It has been found that the "geometrical aggravation factor" is independent of input magnitude showing that, at least in this case, the 2D amplification factors can be regarded as a combination of 1D stratigraphic amplification (including the non-linear effects) and 2D geometrical aggravation.

RÉSUMÉ: La réponse sismique d'une vallée alluviale est principalement régie par une combinaison de facteurs géométriques (par exemple le rapport de forme et l'inclinaison des bords) et stratigraphiques (par exemple le profil de vitesse des ondes de cisaillement et le comportement non linéaire du sol). Habituellement, l'influence de ces paramètres sur l'amplification du mouvement sismique est étudiée en réalisant des analyses numériques 2D ou 3D non linéaires complexes et chronophages. En fait, il n'a pas encore été suffisamment étudié s'il est possible de découpler les deux effets et comment les étudier séparément. Dans cette étude, un ensemble d'analyses numériques 1D et 2D a été réalisé pour étudier l'influence de la non-linéarité sur la réponse sismique des vallées alluviales et tenter d'isoler cet effet de celui des autres paramètres. Une coupe transversale le long de la vallée d'Aterno (L'Aquila - Italie) a été considérée pour construire le modèle 2D d'une vallée trapézoïdale simplifiée. Les résultats des analyses numériques 2D ont été comparés à la réponse 1D le long du profil au centre de la vallée, en termes de rapport entre les facteurs d'amplification spectrale, afin de quantifier l'influence de la géométrie sur la réponse de la vallée. Il a été constaté que le "facteur d'amplification géométrique" est indépendant de la grandeur d'entrée montrant qu'au moins dans ce cas, les facteurs d'aggravation 2D peuvent être considérés comme une combinaison d'amplification stratigraphique 1D (y compris les effets non linéaires) et d'aggravation géométrique 2D.

KEYWORDS: seismic site response, basin effects, alluvial valley.

1 INTRODUCTION

The seismic response of an alluvial valley is influenced by a combination of many factors, such as shape ratio (Bard & Bouchon 1980a,b), inclination of the edges (Zhu & Thambiratnam 2016), impedance ratio (Bard & Bouchon 1985), non-linear soil behaviour (Gelagoti et al. 2010) and characteristics of reference input motion (Alleanza et al. 2019). The main modifications on the surface motion with reference to ideal 1D propagation is related to buried 2D/3D morphology, in particular the inclined contact between bedrock and deformable soil. Indeed, at the edge of the valley a complex interference occurs among the direct, reflected, and refracted waves inducing the generation of spurious surface waves. In particular, SH waves generate Love waves (Aki & Larner 1970, Bard & Bouchon 1980a), while the combination of P and SV waves generates Rayleigh waves (Bard & Bouchon 1980b).

In recent years, numerous studies have been carried out to quantify the amplification of the seismic motion in alluvial valleys and to define an appropriate Aggravation Factor, AF (Riga et al. 2016, Papadimitriou et al. 2018, Papadimitriou 2019, Pitilakis et al. 2019), such as that typically adopted by the codes of practice to quantify topographic amplification. However, an easily calculated AF that can adequately consider the influence of geometry, mechanical and non-linear soil properties on the seismic response has not been defined yet. Usually, to isolate the geometric 2D effects from the stratigraphic ones a geometric aggravation factor is defined, as the ratio between the results obtained from 2D and 1D analyses. Generally, a 2D visco-elastic analysis is carried out assuming that the geometric aggravation factor is not significantly affected by the non-linear properties of the soil. These latter are taken into account in the 1D analysis which allows quantifying the stratigraphic amplification. However, it has not yet been adequately assessed if it is possible to decouple the geometric and stratigraphic effects and how to study them separately.

This study aims to verify the opportunity of computing the site response of a trapezoidal valley as the combination of the non-linear amplification of a 1D soil profile and an aggravation factor based on the results of 2D visco-elastic analyses, thus assuming that non-linearity does not further affect the 2D response of the valley. To validate this hypothesis, the case study of a well-characterized cross-section of the Aterno valley (L'Aquila - Italy) was selected and modelled as a simplified trapezoidal valley.

2 CASE STUDY: ATERNO RIVER VALLEY

L'Aquila (Italy) is an important and densely populated city located on the left bank of the alluvial valley of the Aterno river.

In this area, there is an articulated system of faults that over the years has generated numerous strong earthquakes, the last of which was on 06/04/2009 with a moment magnitude $M_W = 6.1$. Due to the high seismicity of the area, since 1994 an array of 5 accelerometric stations (AQG, AQA, AQV, AQM, AQF) was installed along the SW-NE direction, transversal to the upper Aterno valley (Figure 1a). The seismic response of the instrumented cross-section (Figure 1b) has been studied in detail by means of accurate analyses of the experimental records and numerical simulations by means of 1D and 2D models (e.g. Lanzo et al. 2011, Chamlagain et al. 2013). These latter were supported by an accurate reconstruction of the geometry of the cross-section and a reliable mechanical characterization of the soils filling the valley, based on the careful analysis of:

- 60 continuous-coring boreholes (10 of which intercepting the carbonate bedrock),
- 70 horizontal-to-vertical spectral ratios from noise measurements (HVNSR),
- 2 Down Hole tests (DH) at AQA and AQG stations,
- 1 Cross Hole test (CH) at the AQV station.

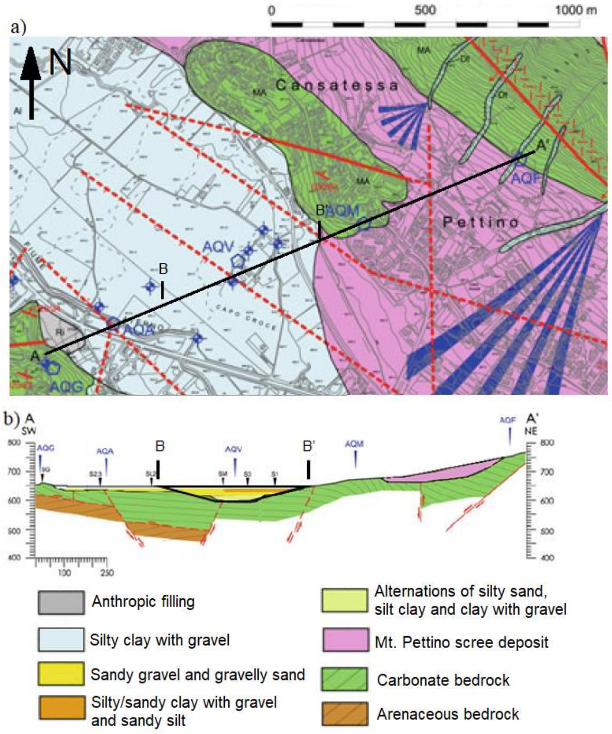

Figure 1. Geological: a) map; b) section (modified from Lanzo et al. 2011).

In this study, the actual valley section was approximated with a trapezoidal symmetrical shape (black line in Figure 1b), with AQV station located in the middle. Due to the complex stratigraphy, two different geotechnical models were considered:

- the first is a heterogeneous model (EM) constituted by parallel horizontal layers, obtained by extending to the whole section the soil stratigraphy and the shear wave velocity, V_S, profile detected by the CH test at AQV station (Figure 2a);
- the second is a homogeneous model (OM) characterized by a single layer with a constant V_S equal to the weighted average of the measured values (Figure 2b).

For both models, the velocity profile at the middle of the valley was considered as the reference soil column to evaluate the 1D stratigraphic amplification.

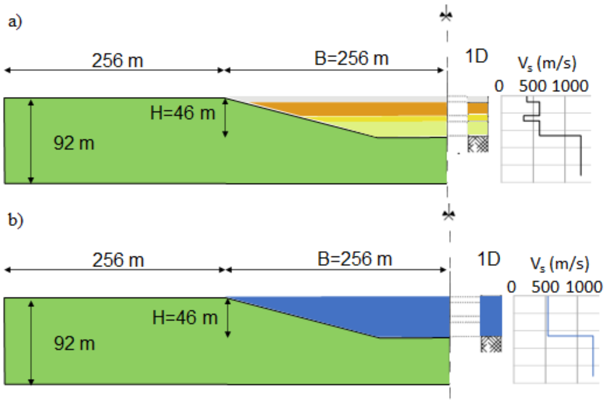

Figure 2. Two-dimensional a) heterogeneous (EM) and b) homogeneous (OM) models; the colour code for the layering in Figure 2a is the same as Figure 1b.

The non-linear behaviour of all soils was characterized based on results of resonant column, RC, test performed on a sample of reconstituted gravelly soil with a fine matrix, obtained from a continuous coring borehole nearby station AQV (Chamlagain et al. 2013). The experimental results were best-fitted using the Ramberg-Osgood, RO, model (Figure 3). A linear visco-elastic behaviour was assumed for the bedrock with a constant damping ratio equal to 0.5%. Table 1-2 summarize the physical and mechanical properties adopted for the subsoil models.

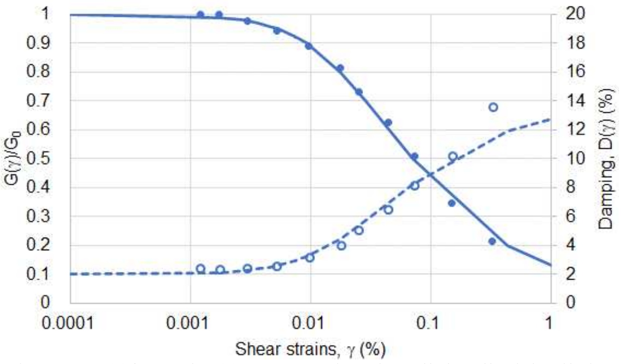

Figure 3. $G(\gamma)/G_0$ and $D(\gamma)$ curves assigned to all the alluvial soils in the numerical analyses (modified from Chamlagain et al. 2013).

Table 1. Physical properties of soils.

Layer	Lithology	Depth (m)	Unit weight γ (kN/m^3)
1	Silty clay with gravel	0-7	19.0
2	Silty/sandy clay with gravel and sandy silt	7-23	
3	Sandy gravel and gravelly sand	23-29	
4	Alternations of silty sand, silt clay with gravel	29-46	
Bedrock	Carbonate bedrock	46-	23.0

Table 2. Elastic and non-linear properties of soils.

Layer	ν	V_S (m/s)		V_P (m/s)		$G(\gamma)/G_0$ and $D(\gamma)$	
		EM	OM	EM	OM	EM	OM
1	0.42	400	537	1077	1446	RO on RC tests (modified from Chamlagain et al. 2013)	
2		600		1616			
3		350		942			
4		600		1616			
Bedrock	0.40	1250		3062		D_0=0.5%	

According to the indications by Bard & Bouchon (1985), the values of the seismic impedance of the soil and a shape factor (the ratio between the thickness, H, and the half-width, B, of the alluvial deposit) as low as 0.18, induce to classify the valley as 'shallow'. This implies that its seismic response in the central part should be mainly characterized by 1D vertical propagation of S waves and their interference with surface waves, without being affected by a global 2D dynamic response, i.e. by higher resonance frequency and peak amplification induced by the focusing of refracted and reflected body waves.

The main shock of 06/04/2009 and 9 aftershocks, recorded at AQG station, were selected as reference input motions and extracted from the Italian seismic database ITACA (D'Amico et al. 2020). The characteristics of the events relevant to the selected signals are reported in Table 3. All the input motions were then projected along the cross-section to maximize the directivity effects of the seismic action. Since the AQG recording station was not located on outcropping bedrock, the projected accelerograms were deconvoluted to the seismic bedrock at a depth of 25m. Figure 4 show the acceleration response spectra of the deconvoluted input motions. It can be noted that the spectral amplitudes span by three orders of magnitude, with the reference peak ground acceleration, PGA_r, varying between 0.002g and 0.245g. Six more accelerograms were added to the selected set, obtained by scaling, after deconvolution, the main event (Acc1 in Table 3) and an aftershock (Acc8 in Table 3) to PGA_r equal to 0.3g, 0.4g and 0.5g, in order to investigate the influence of soil non-linearity on the valley amplification.

Table 3. Event characteristics relevant to the selected accelerograms.

	Date	Time (GMT)	Moment Magnitude M_w	Epicentral distance R_{epi} (km)
Acc1	06/04/09	01:32:40	6.1	5.0
Acc2	06/04/09	01:44:35	3.7 (M_l)	8.6
Acc3	06/04/09	02:27:47	3.9 (M_l)	1.7
Acc4	06/04/09	02:37:04	5.1	1.7
Acc5	06/04/09	03:56:45	4.5	5.9
Acc6	06/04/09	04:47:53	3.8	2.5
Acc7	07/04/09	09:26:28	5.1	5.9
Acc8	07/04/09	17:47:37	5.5	14.6
Acc9	07/04/09	21:34:29	4.5	3.0
Acc10	09/04/09	00:52:59	5.4	12.9

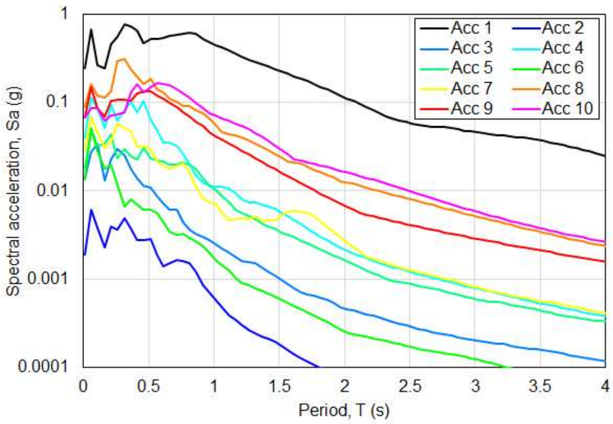

Figure 4. Acceleration response spectra of the deconvoluted input motions

The 2D analyses were carried out with the computer code QUAD4M (Hudson et al. 2003), a finite element program that performs equivalent linear analysis in the time domain. A full Rayleigh damping formulation with a double frequency approach was implemented in the code: the first frequency was set equal to the fundamental frequency of the model, while the second one was obtained by multiplying to the first the odd integer closest to the ratio, approximated by excess, between the predominant frequency of the reference motion and the fundamental one of the model. The input motion was applied at the bottom boundary of the domain in Figure 2a,b, assumed as a transmitting half-space (Hudson et al. 2003). The domain was laterally extended for a length equal to the valley half-width, to minimize undesired effects of fictitious reflections of the seismic waves against lateral boundaries, where horizontally restrained nodes were applied. The mesh consisted of triangular elements, the maximum size of which was defined according to Kuhlemeyer & Lysmer (1973) criterion.

For each 2D analysis, a 1D analysis at the central reference soil column was also carried out, by means of the computer code STRATA (Kottke & Rathje 2008) which performs equivalent linear analyses in the frequency domain.

3 RESULTS

Figure 5 shows the results of 2D analyses carried out on both OM and EM models applying Acc1 scaled to increasing values of PGA. The results are expressed in terms of profiles of PGA amplification along the valley, i.e. the ratio between the maximum acceleration at surface, PGA_s, and at the bedrock, PGA_r. In general, the response of OM model is characterized by lower PGA amplification with respect to EM response. This is more apparent along the edges, where the variability of impedance contrast enhances the interaction among the various wave fields. Furthermore, in both models a substantial decrease of PGA_s is observed at the center of the valley as the mobilized non-linearity increases, while this effect is less significant at the edges. In the middle of the valley, the response is mainly governed by the increase of the damping rather than by the mobilized shear modulus, while at the edges the amplification is mainly related to interference phenomena, not affected by the damping ratio (Gelagoti et al. 2010).

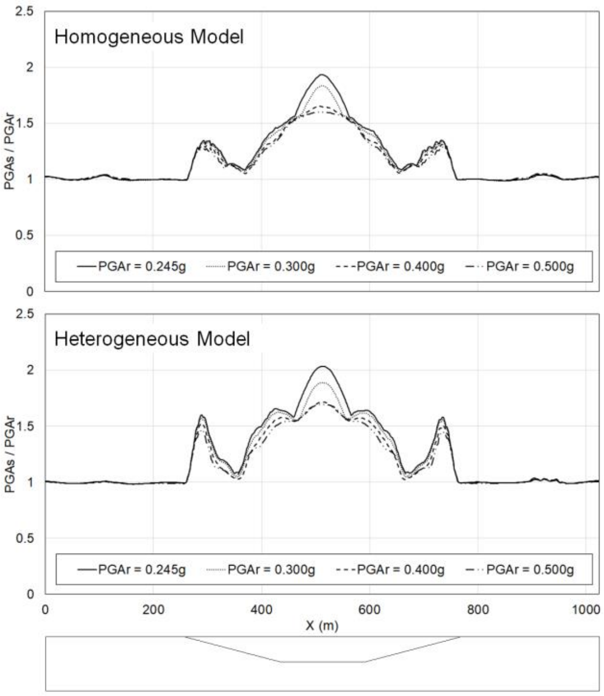

Figure 5. Variation of the ratio between PGA_s and PGA_r along the valley for both models.

Since the effects of non-linearity mostly affect the response at the centre of the valley, in the following the influence of 2D geometry will be investigated with reference to this vertical. The non-linear amplification factors, expressed in terms of ratio between PGA_s and PGA_r, computed performing 2D, $S_{s,2D}$, and 1D, $S_{s,1D}$, analyses, are represented with full dots in Figure 6, as a function of PGA_r. Both amplification factors, $S_{s,2D}$ and $S_{s,1D}$ are almost constant for values of PGA_r not exceeding 0.1g; at higher values of PGA_r they decrease with the mobilization of non-linearity, being the effects of the increasing damping predominant on the amplification related to the increase of impedance ratio due to the reduced soil stiffness.

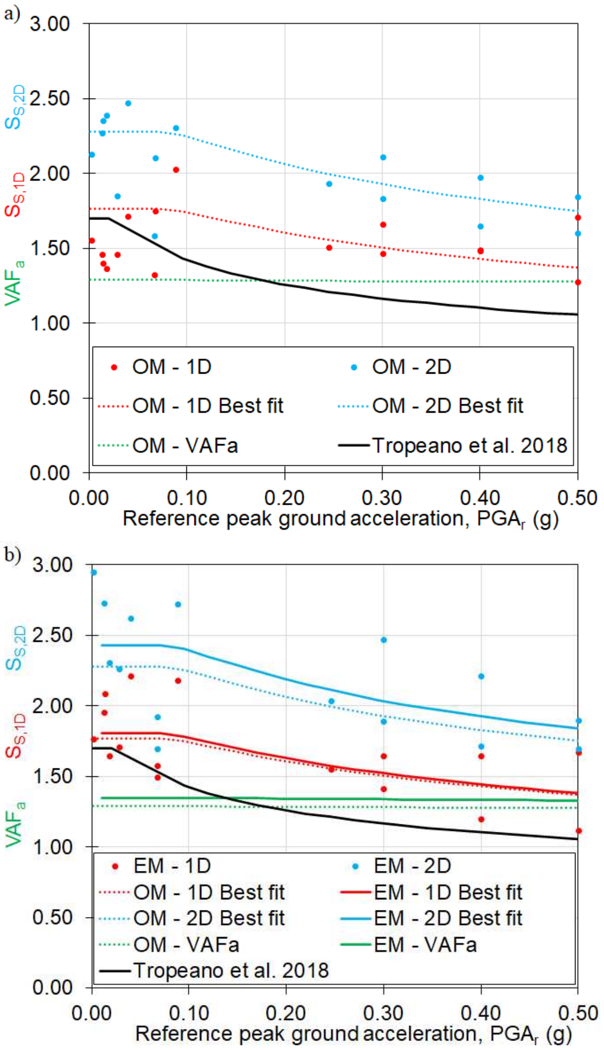

Figure 6. Amplification factors in terms of PGA for: a) homogeneous model; b) heterogeneous model.

Following the procedure adopted by Tropeano et al. (2018), a regression function has been fitted to the data points, using two different expressions to account for the above-described trend. The expression adopted for the general function is:

$$S_S = \begin{cases} m & \mathrm{PGA_r} \leq x_i \\ \frac{a(\mathrm{PGA_r}-x_0)^b}{\mathrm{PGA_r}} & \mathrm{PGA_r} > x_i \end{cases} \tag{1}$$

where: m is the constant initial value of S_S; a, x_0 and b are the parameters of the power function that characterizes the decreasing branch of the regression function; x_i is the value of reference PGA corresponding to the intersection point of the two functions.

For both OM (Figure 6a) and EM (Figure 6b) models it is apparent that the amplification predicted by 1D (red curves) analyses significantly underestimates that resulting from 2D simulations (blue curves). Figure 6b also shows that the homogeneous model (dotted curves) is characterized by amplification factors slightly lower than those computed for the heterogeneous one (solid curves), with the curves relevant to the 1D response about coincident, despite the non-negligible difference between the single data points.

The PGA amplification curves computed in this study are always higher than that suggested by Tropeano et al. (2018) for a ground type B, compatible with the V_S profile, reported in Figures 6a-b with a black line. This latter was evaluated by averaging the results of a large number of data points corresponding to different sets of V_S profiles, non-linear properties and seismic motions. Moreover, most of the reference data consisted of results of 1D analyses on gravelly soils with a degree of non-linearity more pronounced than that characterizing this specific soil (see Figure 3): this justifies the less apparent decrease with PGA_r of the 1D amplification factor in this specific case, after an initial agreement with the mean value predicted by Tropeano et al. (2018). As a matter of fact, in this latter work the data points relevant to the Aterno valley records lie well above the average trend of the amplification values.

In order to quantify the influence of valley geometry, a 'Valley Aggravation Factor' for PGA, VAF_a, is then defined as the ratio between the fitted functions of $S_{s,2D}$ and $S_{s,1D}$. Figures 6a-b show with green lines the VAF_a values computed for both models as a function of PGA_r. Being these ratios about constant, it can be stated that non-linearity does not significantly influence the valley amplification, at least in terms of PGA in this case.

The amplification factor based on a ratio between PGA values is mainly related to the high-frequency seismic response. To evaluate the overall effect of 2D geometry on a broader frequency range it is more appropriate to express amplification in terms of integral ground motion parameters, as often assumed by design codes of practice and guidelines for seismic microzonation (Gruppo di lavoro MS 2008). For this reason, two more alternative formulations of the valley aggravation factor have been considered, i.e. one expressed in terms of ratio between the Housner Intensity, HI, at surface computed in 2D and 1D analyses, VAF_{HI}, and another based on the same ratio in terms of spectral acceleration, VAF_{SA}.

It is worth recalling that the Housner intensity is an integral parameter suitable to evaluate the seismic vulnerability of buildings, because of its representativeness of the energy content of the ground motion related to the structural damage. It is defined as follows:

$$HI = \int_{T_a}^{T_b} PSV(T,\ \xi) \cdot dT \tag{2}$$

where PSV is the pseudo-spectral velocity, ξ is the structural damping, T_a and T_b limit the range of periods of interest. In this study, T_a is assumed equal to 0.1s while T_b is set equal to the fundamental period of the amplification function computed at the center of the valley ($T_{0,1D}$), which therefore may be variable with the reference input motion due to soil non-linearity. This assumption derives from the observation that for periods exceeding $T_{0,1D}$ the two-dimensional effects become negligible (Vessia et al. 2011).

Figure 7 shows the amplification of Housner intensity, i.e. the ratio between HI calculated at the surface, HI_s, and at the bedrock, HI_r, as a function of the latter. This amplification factor has been computed for both 1D, $S_{HI,1D}$, and 2D analyses, $S_{HI,2D}$, again considering the homogeneous (Figure 7a) and heterogeneous (Figure 7b) models. It should be clarified that the reference Housner intensity values computed for the two models (OM and EM) are different because the value of $T_{0,1D}$ depends on the model assumed.

The computed values of the amplification factors have been then fitted adopting the same general form of Eq. 1, except for replacing PGA with HI. Just like those in terms of PGA, even these amplification factors decrease with the energy of the input motion. Again, 2D geometry significantly increases the amplification factor at surface if compared to that computed along a one-dimensional column, while this latter is hardly influenced by heterogeneity, which in turn significantly affects the 2D response. The valley aggravation factor computed with reference to the Housner intensity, i.e. as the ratio VAF_{HI} between $S_{IH,2D}$ and $S_{IH,1D}$, even in this case does not vary with the increasing energy of the input motion, hence it results independent of non-linearity like VAF_a. It assumes slightly higher values in the case of a heterogeneous model. The values of VAF_{HI} are higher than those of VAF_a, implying that the amplification due to valley effects influences less significantly the propagation of high-frequency vibration components, i.e. those with wavelengths negligible with respect to the soil thickness.

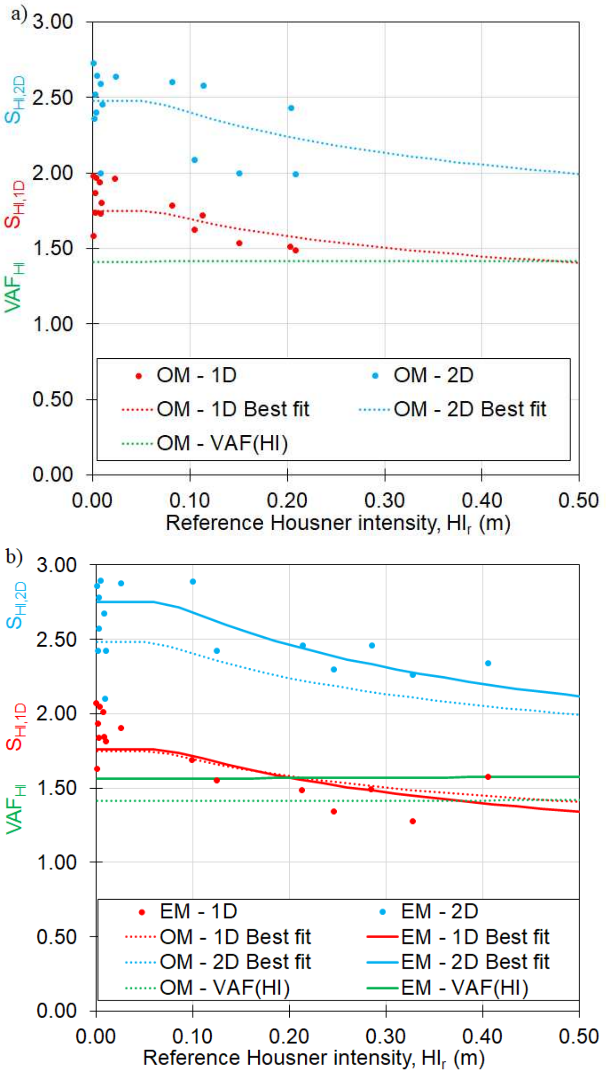

Figure 7. Amplification factors in terms of HI for: a) homogeneous model; b) heterogeneous model.

Following a similar procedure, a spectral intensity was calculated as integral of the acceleration response spectra at surface, SA_s, and bedrock, SA_r, within the same range of periods between 0.1s and $T_{0,1D}$. Likewise, the amplification factor was defined as the ratio between SA_s and SA_r, for both 1D, $S_{SA,1D}$, and 2D, $S_{SA,2D}$, geometries, considering homogeneous and heterogeneous models. Analogous expressions referred to pre-determined ranges of periods are adopted in the current practice for mapping ground motion amplification in seismic microzonation studies in Italy and other countries (Gruppo di lavoro MS 2008). Also in this case the reference spectral amplification values computed for the two models differ due to the different values of $T_{0,1D}$.

The results are shown in Figure 8 together with the fitting functions adopted. Even in this case, the two-dimensional analyses on the heterogeneous model give rise to the highest amplification of the ground motion at the center of the valley. A valley aggravation factor of spectral acceleration, VAF_{SA}, is finally defined as the ratio between $S_{SA,2D}$ and $S_{SA,1D}$. VAF_{SA} is almost constant for both models, confirming that non-linearity does not affect the 2D response at least at the center of the valley.

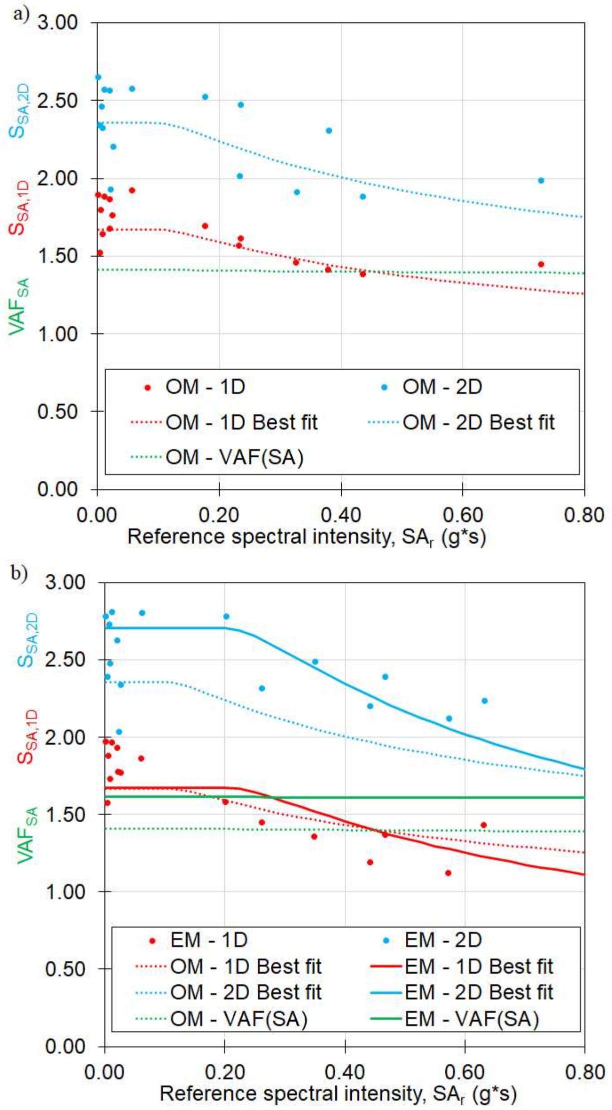

Figure 8. Amplification factors of spectral acceleration for: a) homogeneous model; b) heterogeneous model.

Table 4 reports the values of the different VAF computed for both models. The valley aggravation factors of PGA have lower values if compared to those computed in terms of spectral amplitudes, which, instead, have quite similar values. In any case, all the VAF computed are greater than unity.

Hence, using the results of 1D analysis at the middle of the valley can lead to an underestimation of the amplification of the seismic motion. Indeed, even if this particular valley should be considered in principle as 'shallow' following the criterion by Bard & Bouchon (1985), the 2D resonance effects are not negligible both at the edges and at the centre of the valley.

Table 4. Valley Aggravation Factors.

Model	Mean VAF_a	Mean VAF_{HI}	Mean VAF_{SA}
OM	1.28	1.42	1.40
EM	1.34	1.57	1.61

4 CONCLUSIONS

This study summarizes the results of an extensive numerical analysis on the seismic response of an alluvial valley typical of Central Italy. The case study was considered as representative of an extensive research project, addressed to evaluate the possibility of decoupling the total ground motion amplification in alluvial valleys as the product of two independent effects:

- a 'stratigraphic' amplification, due to the impedance contrast between alluvial soil and underlying bedrock, which is affected by soil non-linearity and can be predicted through a 1D analysis or expressed by soil factors decreasing with the seismic motion amplitude;
- a 'valley' aggravation factor, due to the irregular buried morphology of the bedrock, which is independent of soil non-linear behavior and can be mainly related to geometrical parameters.

The geometrical, mechanical, and non-linear soil properties used in the study were taken from the well-known accelerometric array deployed across the Aterno valley. A simplified trapezoidal scheme of this valley was defined to carry out a set of non-linear 2D numerical analyses. A reference 1D column was extracted from the middle of the valley to evaluate the effects of the stratigraphic amplification. Several accelerograms recorded on a rock outcrop were used as input motions. Some of them were scaled by increasing the maximum acceleration to investigate the influence of non-linearity on the seismic response at the surface.

Three different Valley Aggravation Factors were defined as ratios between peak (PGA) or integral (HI, SA) ground motion parameters obtained from 2D and 1D analyses. The results show that the geometrical effect is underestimated if evaluated through the valley aggravation factor of PGA, since this latter takes into account the influence of 2D geometry only on the peak value and the highest frequency content of the accelerogram. On the other hand, the VAF based on integral parameters in terms of spectral velocity or acceleration accounts for a wide frequency content of the input.

In any case, all the computed VAF are significantly greater than unity, hence the amplification at the middle of a shallow valley cannot be assumed as purely stratigraphic and not affected by the buried valley morphology. Nevertheless, all the VAF computed are constant with the increase of the energy of the input motion, thus independent of soil non-linearity.

Hence, for this well-documented case study, it was confirmed that the total amplification at the center of the valley can be decoupled in two independent factors and calculated by multiplying the VAF by the results obtained with a 1D equivalent linear analysis.

5 ACKNOWLEDGEMENTS

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