EXTENSIVE NUMERICAL STUDY ON IDENTIFICATION OF KEY STRUCTURAL PARAMETERS RESPONSIBLE FOR SITE EFFECTS

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ABSTRACT

SIGMA, a R&D program of EDF, AREVA, CEA and ENEL in 2011-2015, aimed to obtain robust and stable estimates of the seismic hazard. The Work Package 3 focused on estimating the amplification effects of local site conditions on earthquake ground motion (EGM). We investigated potential of typical 2D and 3D geometries of the underground structure to undergo site effects. We performed 1D, 2D and 3D simulations for 6 typical models of sedimentary valleys and a variety of their modifications to investigate EGM sensitivity to geometry, impedance contrast, attenuation, velocity gradient and small-scale random heterogeneities in sediments. We calculated amplification factors, and 2D/1D and 3D/2D aggravation factors for 10 EGM characteristics, using a representative set of recorded accelerograms to account for input motion variability. The largest values of the amplification and aggravation factors are found for the Arias intensity and cumulative absolute velocity, the lowest for the root-mean-square acceleration. The aggravation factors are largest for the vertical component. For each model, at least one EGM characteristic exhibits a significant 2D/1D aggravation factor, while all EGM characteristics exhibit significant 2D/1D aggravation factor on the vertical component. For all sites, there is always an area in the valley for which 1D estimates are not sufficient. 2D estimates are insufficient at several sites. The key structural parameters are the shape ratio and overall geometry of the sediment-bedrock interface, impedance contrast at the sediment-bedrock interface, and attenuation in sediments. The amplification factors may largely exceed values considered in GMPEs between soft soils and rock sites.

Keywords: numerical simulations, site effects, earthquake ground motion characteristics, random media

1. INTRODUCTION

A large number of cities or critical facilities are located in alluvial valleys or sedimentary basins with pronounced 2D or 3D underground geometry. Lateral variations of thickness in alluvial valleys or basins have been shown to generate peculiar wave propagation phenomena (diffraction of surface waves, possible focusing of body waves, vertical and lateral reverberations) leading to increased wave trapping and interferences, and significant differences (increased duration, mostly overamplification, sometimes deamplification) with respect to the case of horizontally stratified layers ("1D soil columns"). However, these effects are rarely accounted for even in site-specific studies because of a) the cost of the required geophysical surveys to constrain the site model, b) lack of data for empirical prediction, and c) poor knowledge of the key controlling parameters. The last issue has been addressed in a number of recent studies. Despite the significance of the associated computational efforts, there is not yet a wide consensus on the key controlling parameters and the quantification of their effects on EGM.

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Consequently, we are still far from accounting these effects in the building codes.

Here we report results of investigation based on extensive numerical simulations and aiming to answer two main questions: a) what could be the amount of actual amplification for realistic situations, especially as it may exceed by far what is predicted by GMPEs based on simple, 1D site proxies?, b) in which case is the aggravation factor significant, or in other words, when 2D or 3D site response studies should be required?

2. SITES AND COMPUTATIONS

We considered 6 nominal models: Site 1 (Mygdonian basin, near Thessaloniki, Greece) – a shallow sediment-filled basin, Site 2 (Grenoble valley, France) – a typical deep Alpine sediment-filled valley, Site 4 – a small shallow sediment-filled valley, Site 5 – a mid-size sediment-filled valley, Site 6 – a relatively small shallow sediment-filled valley, and Site 7 – a shallow relatively large sediment-filled valley. In addition to the 6 "nominal models" we defined a variety of modifications in order to investigate sensitivity of EGM to sediment-bedrock interface geometry, impedance contrast, attenuation, velocity gradient and small-scale random heterogeneities in sediments.

In order to analyse EGM in relation to the chosen variety of subsurface models and their structural parameters, we investigated amplification and aggravation factors for 10 EGM characteristics selected because of their engineering relevance for such a comparison.

For evaluating the amplification and aggravation factors it is necessary to compute first an acceleration at a site of interest. Having no or insufficient number of records at the investigated sites we have to account for a potential input motion variability. It is reasonable to use a set of properly selected accelerograms recorded at different locations. In our computations we assume that the selected records represent EGM at a free surface of a halfspace, that is, they are not affected by the local conditions at the site of interest. Kristek et al. (2018) presented a method to calculate acceleration at a site of interest corresponding to a record at the free surface of a homogeneous halfspace based on the forward numerical simulations of EGM in a model comprising the local surface structure and in the model of the homogeneous halfspace.

Forward numerical simulations of EGM were performed in the linear domain with the finite-difference (FD) method (Moczo et al. 2014, Kristek and Moczo 2014, Chaljub et al. 2010, 2015). 3D simulations were performed for Sites 1, 2 and 6, assuming a vertical plane wave incidence as well as several point double-couple (DC) sources located at different positions. 2D simulations were performed for selected 2D profiles in the 3D models (Sites 1 and 2) and also all other 2D nominal models and their variants (Sites 4 to 7) assuming the vertical plane wave incidence. 1D simulations have been performed with 1D models corresponding to all the selected receiver positions along all the 2D profiles.

2.1. Sites and nominal models

2.1.1. 3D models

The Mygdonian basin (Site 1, shown in Figure 1a) is a relatively shallow sedimentary basin with gentle slopes and complicated geometry of the sediment-bedrock interface, relatively low $V_S$ (S-wave speed) near the surface (130 m/s), large impedance contrast between sediments and bedrock (from 3 to 18), $V_P / V_S$ larger than 10 at the surface. Extensive surface waves can be generated in the basin. Three distinct 2D profiles (E, C and W) were selected for detail investigation. The Grenoble valley (Site 2, shown in Figure 1b) is a typical deep Alpine sediment-filled valley with a complicated geometry of the sediment-bedrock interface, relatively low $V_S$ near the surface (320 m/s), large sediment-bedrock impedance contrast (from 3.5 to 10), and almost 7 at the surface. 2D or 3D low-frequency resonances might develop. Four distinct 2D profiles (P1 – P4) were selected.

2.1.2. 2D models

Sites 4 is the smallest of the investigated sedimentary structures (max. thickness 120 m, width 920 m)
with velocity gradient in sediments. Site 5 is the mid-size, deep sediment-filled valley (max. thickness 581 m, width 3.5 km) with relatively strong velocity gradient in sediments and relatively large sediment-bedrock impedance contrast. Site 6 is the intermediate size (max. thickness 161 m, width 2.2 km) with a thin low-velocity layer at the surface and large sediment-bedrock impedance contrast. For Site 6 there are 2 alternative models: one with a thin, soft, 5 m-thick layer with a S-wave speed 230 m/s overlying homogeneous sediments with the 600 m/s S-wave speed, one with the same top thin, soft layer, overlying sediments with a gradient in the P- and S-wave speeds. Site 7 is the relatively large, shallow valley (max. thickness 510 m, width 6.2 km) with 3 sedimentary layers, two of them with strong gradients and large sediment-bedrock impedance contrast.

The 7 selected profiles in the Mygdonian basin and Grenoble valley make 12 2D models (Figure 2). Selected mechanical and geometrical parameters are shown in Figure 3. For more see Moczo et al. (2018) and Kristek et al. (2015).

Figure 1. Sediment-bedrock interface in the models of: a) Mygdonian basin. The red frame shows the area of the computational model. E, C and W: selected profiles. Depicted area: approx. 65 x 48 km². b) Grenoble valley. The red stars: A, B and C positions of the point DC sources. P1 – P4: selected profiles.
Depicted area: approx. 27 x 30 km².

2.2. Modified models for sensitivity studies

The modifications of the nominal models with respect to important selected structural parameters include:

- a high-velocity layer at the free surface of the Site 2,
- alternative attenuation parameters in the:
  - Site 2 (Grenoble valley) models – derived from 1D nonlinear simulations to investigate the impact of larger attenuation throughout the very thick deposits,
  - Sites 5 – 7 models – perfectly elastic, \( Q_3 = V_S / 20 \), \( Q_5 = V_S / 40 \),
- alternative sloping angles for the sediment-bedrock interface in the P1, Site 5 and Site 6 models,
- alternative bedrock velocities in the Sites 5 – 7 models, and alternative velocities in sediments in Site 6 model,
- simultaneous variations in the velocity and thickness of sediments in the Site 6 model keeping the fixed local 1D fundamental resonant frequency; the sediment P-wave velocity kept unchanged – corresponding to high Poisson ratio, water saturated sediments,
- 3D meander (S-shape) extensions of the S6 models; these 3D models together with the Site 1 and 2 models make it possible to quantify the differences between 2D and 3D site responses.
We also include modifications of the nominal models consisting in small-scale random heterogenization of P-wave and S-wave speeds, and density in sediments. We consider 3 different autocorrelation functions which are commonly used to study wave propagation in random media – Gaussian, exponential and von-Kármán (we use functions proposed by Frankel and Clayton 1986). They differ in the spectral falloff of their power spectra. We consider 3 different values of standard deviation (5%, 10% and 20%) and fixed values of correlation lengths with a vertical-to-horizontal ratio 1:10. For each of 9 combinations of the standard deviation and autocorrelation function we generated 10 modified models.

As previously indicated, we also consider 3 hypocentral positions of a point DC source in the Site 2 model in order to compare EGM due to plane-wave incidence with EGM due to point sources.

Figure 2. Geometry of the sediment-bedrock interface and S-wave speed distribution in the 7 profiles. The horizontal-to-vertical scale is 1:1. The S-wave speed is shown using colour scale by Niccoli (2014).

N: North, S: South, W: West, E: East.

3. OVERVIEW OF CALCULATED EGM AGGRAVATION FACTORS FOR NOMINAL MODELS

The following EGM scalar characteristics for each component of ground motion were evaluated for the
nominal models (Figure 4): $\overline{AF}\{pga\}, \overline{AF}\{pgv\}, \overline{F}_A, \overline{F}_V, \overline{F}_0, \overline{F}_L, \overline{AF}\{a_{rms}\}, \overline{AF}\{SI\}, \overline{AF}\{CAV\}$ and $\overline{AF}\{I_A\}$. The EGM characteristics for 3D simulations were calculated in the frequency ranges $0.5 – 5$ Hz for Sites 1 and 2, and $0.5 – 7$ Hz for Site 6. The characteristics for 2D and 1D simulations were calculated in the frequency range $0.2 – 20$ Hz for all Sites, and also in the frequency ranges $0.5 – 5$ Hz and $0.5 – 7$ Hz for respective comparisons with the 3D simulations for Sites 1, 2 and 6. To quantify differences between results from 3D and 2D numerical simulation, a 3D/2D aggravation factor was defined as a ratio of values of the EGM characteristics obtained from 3D and 2D numerical simulations for a given position at a site. Analogously, a 2D/1D aggravation factor compares values of an EGM characteristic obtained from 2D and 1D simulations. For brevity we will use abbreviation AGF for the aggravation factor(s).

![Figure 3. Selected mechanical and geometrical parameters in 3D and 2D models.](image)

<table>
<thead>
<tr>
<th>Site</th>
<th>Profile</th>
<th>$V_{S min}$</th>
<th>$V_{S 30}$</th>
<th>$\overline{V}_S$</th>
<th>$w$</th>
<th>$z_{max}$</th>
<th>$V_{S b}$</th>
<th>$f_{00}$</th>
<th>$z_{max}/w$</th>
<th>$V_{S b}/V_{S 30}$</th>
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<td>180</td>
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<td>C</td>
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<td>245</td>
<td>445</td>
<td>4900</td>
<td>266</td>
<td>2000</td>
<td>0.5</td>
<td>0.05</td>
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<td>W</td>
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<td>520</td>
<td>745</td>
<td>393</td>
<td>0.7</td>
<td>250</td>
<td>0.5</td>
<td>0.05</td>
<td>15</td>
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<td>0.2</td>
<td>0.3</td>
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<td>6590</td>
<td>670</td>
<td>3200</td>
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<td>120</td>
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<td>920</td>
<td>3500</td>
<td>581</td>
<td>gradient</td>
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<td>0.2</td>
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</tr>
<tr>
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<td>540</td>
<td>590</td>
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<td>510</td>
<td>2800</td>
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at all sites $Q_S = V_S / 10$. $Q_{S b} = \infty$

gradient at Site 5: $V_{S b}(z) = 1050 + 1.3125z$

Figure 4. Overview of the calculated earthquake ground motion characteristics

$S_D$ – relative displacement response spectrum, $pga$ – peak ground acceleration
$pgv$ – peak ground velocity, $CAV$ – cumulative absolute velocity, $I_A$ – Arias intensity
$a_{rms}$ – root-mean-square acceleration, $SI$ – spectrum intensity. Averaged amplification factors:
$\overline{F}_A$ – short-period, $\overline{F}_V$ – long-period, $\overline{F}_0$ – $f_{00}$-centred, $\overline{F}_L$ – $f_0$-centred. $f_0$ – a local 1D fundamental resonant frequency, $f_{00} = \min \{f_i\}$

Figure 5a shows AGF of the 10 EGM characteristics at receiver positions at rock outcrop. The significant majority of values below 1.25 led us to choose this value as a reasonable level above which
the value of an AGF is considered significant. Figure 5b shows the AGF at receiver positions atop sediments. For all sites there is at least one EGM characteristic with significant 2D/1D AGF. The 2D/1D factors for the anti-plane and in-plane components are comparable while they are considerably larger on the vertical component. All characteristics exhibit significant 2D/1D AGF on the vertical component. This strongly suggests that 1D modelling significantly underestimates vertical component of EGM. The variability of 3D/2D AGF show that 3D effects are present both in the Grenoble valley and Mygdonian basin. Their values are considerably smaller (and are actually lower than 1 for quite many sites) than the 2D/1D AGF (which are, however, evaluated in a broader frequency range). Difference between the 3D/2D AGF on the horizontal and vertical components is considerably smaller compared to the 2D/1D factors.

![Figure 5a](image)

Figure 5a. 2D/1D and 3D/2D aggravation factors for 10 EGM characteristics calculated for the nominal models. Each point represents a value at one receiver position at rock outcrop.

Figure 6a shows 2D/1D AGF for $\overline{AF\{CAV\}}$ in the frequency range [0.2-20] Hz for all profiles ordered according to the value of the shape ratio (maximum sediment thickness over width). The 2D/1D AGF are significant on all components at all receivers atop sediments. The AGF on the vertical component are significantly larger than those on the horizontal components. The mean and median values of the AGF on the in-plane component are smaller than those on the anti-plane component. The AGF are not related to the shape ratio or velocity contrast in a simple way. Figure 6b shows 3D/2D
aggravation factors for $\overline{AF} \{CAV\}$. 3D effects are significant in the Grenoble valley (Site 2, profiles P1 – P4, in blue). They are present also in the Mygdonian basin (Site 1, profiles E,C,W, in brown) but they are not dominant. Unlike the 2D/1D AGF, the vertical component does not significantly differ from the horizontal ones.

Descriptive statistical analysis was performed to find out potential correlations between EGM characteristics to select independent ones. The scatter matrices and values of correlation coefficients led to selection of $\overline{F}_A$, $\overline{F}_V$, $\overline{F}_L$ and $\overline{AF}\{CAV\}$; see Moczo et al. (2018) for more details.

Figure 5b. 2D/1D and 3D/2D aggravation factors for 10 EGM characteristics calculated for the nominal models. Each point represents a value at one receiver position atop sediments. Excluded are receiver positions in case of the local fundamental frequency larger than 20 Hz.

4. EFFECTS OF STRUCTURAL-PARAMETER VARIATIONS ON THE AGGRAVATION AND AMPLIFICATION FACTORS

Here we briefly summarize major results from the sensitivity investigations according to the structural parameters and type of wavefield excitation.
**Effect of variation in bedrock velocity.** The AGF (and the amplifications factors) increase with the velocity contrast at deeper part of the sediment-bedrock interface, and this increase is larger for the vertical component. This is mainly true at frequencies close to the fundamental resonant frequency.

**Effect of sediment velocity.** The effect of presence of the high-velocity surface layer in the Site-2 model on the 3D/2D and 2D/1D aggravation factors is negligible for AGF and the amplification factors. The difference between the velocity distributions in sediments in models S6h (homogeneous) and S6g (gradient) has no effect on the 2D/1D AGF, while it does imply a small difference in the amplification factors for S6h and S6g, which can be attributed to the difference in the impedance contrast at the sediment-bedrock interface (due to different velocity distribution in sediments).

![Graph showing the effect of bedrock velocity contrast on AGF and amplification factors.](image)

Figure 6a. 2D/1D aggravation factor for $AF\{CAV\}$ in the frequency range [0.2-20] Hz for all profiles ordered according to the value of the shape ratio (maximum sediment thickness over width). The colour indicates the sediment / bedrock velocity contrast.

**Effect of attenuation in sediments.** The 2D/1D AGF decreases with increasing sediment attenuation since the “over-amplification” in 2D valleys is related to the generation and propagation of surface waves and their propagation is sensitive to sediment attenuation. The amplification factor decreases with increasing attenuation because the increased dissipation in sediments lessens the effect of wave trapping. Decrease of AGF is slightly less sensitive to variations in the attenuation than that of the amplification factor for horizontal components, since the 1D response is also significantly reduced by increased
attenuation.

**Effect of the simultaneous variations in velocity and thickness of sediments.** The simultaneous variations by ± 40% keep the fundamental resonant frequency unchanged. The increase of the impedance contrast in the $V_S \& h - 40\%$ modification causes the increase in the amplification factor. The 2D/1D AGF are slightly less sensitive to modifications in both velocities and thicknesses of sediments than the amplification factors are.

**Effect of geometry of the border slope.** The effect of the border slope is evident close to the valley border for the amplification factor because the modified geometry significantly changes the thickness of the local soil columns. It is insignificant away from the border. The AGF is insensitive.

**Effect of the 3D meander-like extension.** The particular meander-type geometry does not impact much the response in the frequency range of [0.5, 7] Hz assuming a plane-wave incidence.

**Effect of the wavefield excitation.** The usual and simple vertically incident plane wave assumption allows to obtain robust estimates of the amplification factors with respect to those obtained for point DC sources with specific hypocentral positions. If the location of potential seismic sources is unknown, an additional variability in site response (± 10%) could be considered.

**Effect of the small-scale random heterogeneities in sediments.** The computational demands for all modified models are large. Therefore, we report here only preliminary results for profile C. Comparison of the 2D/1D AGF for $\text{AF}_C$ for the nominal and modified models is shown in Figure 7. There is no significant change in the AGF values for the 5% standard deviation. The AGF, however, increases with increasing standard deviation. For the 20% standard deviation the AGF for the models with randomly heterogeneous sediments are considerably larger than those for the nominal model. The same is also true for the AGF for 3 other uncorrelated EGM characteristics.

5. **CONCLUSIONS**

The values of amplification and aggravation factors depend on the considered EGM characteristic. The largest values are found for the Arias intensity $I_A$, ahead of the cumulative absolute velocity $C A V$, lowest values are found for the root mean square acceleration. (For brevity, also here we will use abbreviation AGF for the aggravation factor or factors)

For all the considered sites, there is at least one surface point for which at least one EGM characteristic exhibits a significant 2D/1D AGF (i.e., larger than 1.25). The 2D/1D AGF are component dependent: they are found systematically the largest for the vertical component, and the smallest for the in-plane component.

For the 3 considered sites, the 2D/1D AGF are considerably larger than the 3D/2D factors. 3D effects are found the most pronounced mainly in the Grenoble site (Site 2) because of the Y shape which cannot be approximated by a 2D profile (profile P4). However, even for such a complex 3D site, the classical, vertically impinging plane wave assumption, is found to provide rather robust and reliable estimates of the amplification factors. The plane-wave excitations should not, however, replace a point DC source (or an extended source) if such source is identified to represent a potential excitation for a given 3D site.

The main partial conclusion is that 1D estimates of EGM characteristics are not sufficient at any of the investigated sites.

We identified the following key structural parameters:

- As expected an AGF is found to increase with the shape ratio (maximum thickness over valley width). Nevertheless, even relatively shallow valleys (shape ratios as low as 0.05) can lead to significant AGF in case of relatively wide, shallow sloping edge (Site 1, see also Chaljub et al. 2015; Maufroy et al. 2015, 2016, 2017). It is thus important to estimate not only the overall shape ratio, but also the overall geometry of the sediment-bedrock interface, in particular the sloping angles of the sediment-bedrock interface on the valley edges.
- The impedance contrast at the sediment-bedrock interface is found to impact not only the amplification factor, as expected, but also AGF: for a given geometry, the larger the impedance contrast, the larger the AGF. This is interpreted as related to the more efficient generation and
trapping of surface waves.
- The attenuation in sediments is found to impact both the amplification factors and AGF: larger attenuation decreases their values, especially on the vertical component.
- Finally, it is found that, due to geometrical effects, the amplification factors may largely exceed the values that are usually considered in GMPEs between soft soils and rock sites: this should be kept in mind when dealing with the design of critical, nuclear-like facilities.

A preliminary conclusion on the effect of the small-scale random heterogeneities of the P- and S-wave speeds and density: the random heterogeneities increase the AGF and amplification factors for all uncorrelated EGM characteristics mainly on the vertical component. The larger is the standard deviation, the larger is the increase.

![Figure 6b. 3D/2D aggravation factor for $\overline{AF} \{CAV\}$ in the frequency range [0.5-5] Hz for all profiles ordered according to the value of the shape ratio (maximum sediment thickness over width). Brown: Site 1, blue: Site 2.](image)

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7. REFERENCES


Figure 7. Comparison of the 2D/1D AGF for $\bar{\mathcal{F}} \{ CAV \}$ for profile C. Each row corresponds to one type of the autocorrelation function. Each column corresponds to one value of the standard deviation. For each of 9 combinations of the standard deviation and autocorrelation function we generated 10 modified models. Each point corresponds to one model and one receiver position atop sediments. Excluded are positions with the local fundamental frequency larger than 20 Hz.