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Model dimensionality effects on the amplification of seismic waves

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ABSTRACT

Despite recent advances in numerical methods and computer architectures that make it ever more practical to obtain computationally the surface response to idealized or realistic seismic events, while fully accounting for three-dimensional effects due to topography or to heterogeneities, reliance on one-dimensional models persists. As discrepancies between computed and recorded responses still remain, in this study we aim at highlighting the effect the model dimensionality choice has on the discrepancies, in the presence of topographic features and/or heterogeneity.

First, we briefly discuss the components of an integrated seismic-motion simulator that deploys best-practice tools for the study of wave amplification in arbitrarily heterogeneous sedimentary basins, while also accounting for topography. Then, we report numerical experiments in two and three dimensions for various prototype topography-endowed and layered domains, and compare the motion amplification/de-amplification patterns against one-dimensional simulations, in order to quantify the effects model dimensionality has on surface motion. We conclude that one-dimensional models greatly underestimate the effects of topography and heterogeneity on the amplification of seismic waves; two-dimensional models fair better, but, in general, they too underestimate the response. It appears that, in the presence of topography and complex stratification, there is no suitable alternative other than three-dimensional models to account for reasonable estimates of motion amplification to guide the design of earthquake-resistant structures.

1. Introduction

The modeling of seismic wave motion within a heterogeneous volume of the earth's upper crust, terminated at an irregular surface (Fig. 1(a)), is often oversimplified by adopting a flat-surface model consisting of horizontal semi-infinite layers and a seismic source that transmits vertically propagating plane waves, as shown in Fig. 1(b). Such simplifications may allow for the use of reduced dimensionality models (1D or 2D), which, however, tend to underestimate motion amplification and fail to adequately capture the motion complexity associated with the physical setting (Fig. 1(a)). While many of the discrepancies reported between observations and computed responses can be attributed to the uncertainties associated with the velocity model (material properties) of a given site, model choices also play a role in the discrepancies. In this article, we highlight the effects model dimensionality has on the motion amplification, in the presence of topographic features or soil heterogeneity.

Numerous documented observations following large earthquakes point to the fact that local site conditions may induce amplification and result in significant motion variability in space. Examples include: Pratt et al. [1] observed an amplification of up to 16 for the ground motions from the Chi-Chi earthquake in the Seattle basin; Çelebi [2] reported a frequency-dependent amplification of seismic waves due to the surface topography in the 1985 Chile earthquake; Çelebi [3] addressed topographic amplification for a particular range of frequencies; Hartzell et al. [4] and Bouchon and Barker [5] documented several topographic amplifications in California; Assimaki et al. [6,7] observed seismic amplifications in the vicinity of a cliff crest during the 1999 Athens earthquake in Greece and claimed that this amplification can only be predicted by simultaneously accounting for the topographic geometry, stratigraphy, and nonlinearity; Graizer [8] showed that the observed amplification at the Tarzana Hill station from the 1987 Whittier Narrows and the 1994 Northridge earthquakes were due to the combined effects of topography and layering that resulted in trapped energy within a low-velocity layer near the surface; Imperatori and Mai [9] showed via numerical simulation of the Swiss alpine region that topography and heterogeneity excites surface motion, particularly around 1 Hz. Further reviews on observations on seismic amplification can be found in Massa et al. [10], and Buech et al. [11].

Several studies have shown that numerical solutions underestimate

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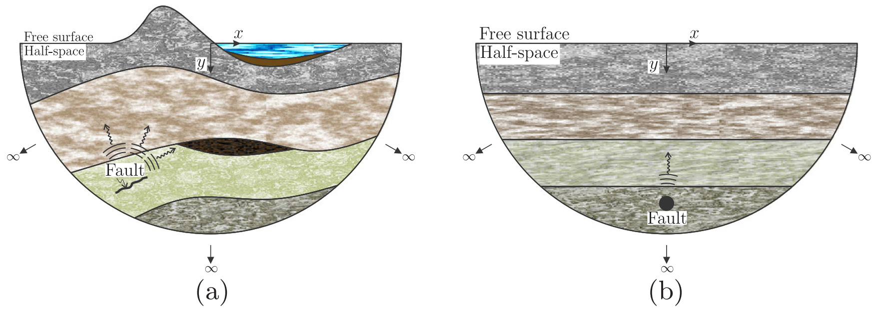

Fig. 1. Seismic domain of interest: (a) physically-faithful idealization; (b) simplified idealization.

seismic wave amplification. Geli et al. [12] compared experimental observations with theoretical results and concluded that the numerical simulations underestimate the topographic amplifications in most cases, mainly because of the oversimplified assumptions considered in the computational models. Bard [13], based on field evidence and theoretical results, claimed that while there is qualitative agreement between theory and observations, larger amplifications are seen in the field. Semblat et al. [14] focused on the influence of the soil layering complexity on site effects. The authors argued that the geometry of the basin has a strong impact on the amplification of seismic waves and on the lengthening of the shaking duration. Field [15] attributed the spectral amplification variability in a sedimentary valley to the basin-edge-induced waves.

The effects of topography, basin geometry, and stratigraphy have also been studied, more often in isolation of each other, than in combination. For example, one of the earliest attempts at tackling wave scattering due to 3D topographic irregularities is the semi-analytical approach discussed in Sánchez-Sesma [16] for axisymmetric surface features. Dravinski et al. [17] used a boundary element method to study a single-layer sedimentary basin subjected to P, SV, and SH plane waves; Sánchez-Sesma and Luzón [18] analyzed the response of Rayleigh, P- and S- waves in three-dimensional alluvial valleys, while Vai et al. [19] simulated wave propagation in irregularly layered, elastic, two-dimensional media with internal line sources. More recently, Assimaki et al. [6] affirmed the significance of topography by performing a time-domain parametric study on a single slope geometry. They concluded that the frequency content of the excitation, the stratigraphy, and the geometry of the cliff are all important in the amplification of incoming seismic waves. Bouckovalas and Papadimitriou [20] discussed the effects of a step-slope topography on the amplification of vertically propagating SV-waves in the frequency domain; Semblat et al. [14] and Makra et al. [21] studied seismic wave amplification in the Volvi (Greece) site to conclude that the basin's geometry strongly affects motion amplification and motion duration, while Meza-Fajardo et al. [22] obtained amplification factors for 3D alluvial basins compared to 1D models, also in the frequency domain.

Poursartip et al. [23] explored the effects two-dimensional hills and valleys have on the amplification of plane SV- and P-waves via parametric studies in the frequency domain. They classified the influence of a variety of parameters, such as wave frequency, angle of incidence, geometry, and wave types, on the amplification/de-amplification of seismic waves. More recently, Wood and Cox [24] exploited ground shaking generated by the controlled collapse of a coal mine in Utah and reported topography-related effects.

Though several studies targeted the effects of heterogeneity or topography on the amplification of the seismic waves, to date there is limited research studying the differences in the response between the still widely used one-dimensional models and fully three-dimensional models. Notable exceptions include: Makra and Chávez-García [25], who investigated the site effects in the Mygdonian basin in northern Greece using a 3D simulation and compared the results with 1D and 2D models to conclude that, while 2D and 3D models are largely similar, the 2D model may overestimate the amplification locally. They also claimed that the 1D model underestimates the amplification and motion duration rather remarkably. Riepl et al. [26] compared various 1D and 2D techniques to simulate site effects in basins. Hisada and Yamamoto [27] and Bielak et al. [28] investigated dimensionality effects in a single, elastic layer underlain by an elastic halfspace using harmonic SH waves. Their results indicate that the 1D model exhibits lower amplification and shorter duration than the corresponding 2D and 3D responses. Moreover, they claimed that the destructive interference of waves in 2D and 3D models in certain locations may result in lower amplification compared to the 1D model. Smerzini et al. [29] and Madiai et al. [30] surveyed dimensionality effects in locations in Italy.

Among the various numerical methods that can be used to simulate seismic wave motion, such as finite differences, boundary elements, etc., the spectral element method is possibly better suited, owing to its flexibility in handling heterogeneous domains with complex geometry and its efficiency in parallel implementations (for a review of numerical approaches to seismic simulation see also Semblat [31]). Examples include: Komatitsch and Tromp [32], Komatitsch and Vilotte [33], Peter et al. [34], Poursartip and Kallivokas [35] and Fathi et al. [36]. In order to negotiate the extent of the semi-infinite domain –a key challenge in seismic motion simulations – one can use non-reflecting boundaries as in Kallivokas et al. [37], Bielak et al. [38], Givoli and Neta [39], Hagstrom and Warburton [40], or Perfectly-Matched-Layers –our preferred choice– as in Kucukcoban and Kallivokas [41], and Fathi et al. [36].

The purpose of this study is to investigate the effects model dimensionality may impose on the amplification of seismic waves, by comparing various one-, two-, and three-dimensional prototype models. Towards this end, we developed a spectral element parallel code which is using best-practice tools for wave motion simulation in the time-domain: we deploy Perfectly-Matched-Layers (PML) for truncating the semi-infinite extent of the domain; we introduce the seismic waves within the computational domain via the Domain-Reduction-Method (DRM) [42–45]; we couple the DRM with the PML; and, additionally, we introduce an adaptive time integration scheme that improves the efficiency of the time-domain simulations, particularly for irregular domains where determination of the optimal time-step that leads to a numerically stable solution requires a trial and error approach. Once the numerical tool is verified against known analytical solutions, we use synthetic models endowed with heterogeneity and surface irregularities, to compare the seismic wave amplifications in one-, two-, and three-dimensional domains in order to assess the importance of model dimensionality choice on the surface response.

2. Numerical modeling

To tackle seismic wave simulation within domains exhibiting heterogeneities and/or topographical features, we discuss next the key points of an integrated software toolchain that includes Perfectly-Matched-Layers (PMLs) for limiting the computational domain; unstructured spectral elements for spatial discretization; seismic source