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Seismic wave amplification by topographic features: A parametric study

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ABSTRACT

Despite the ever increasing adoption of wave motion simulations for assessing seismic hazard, most assessment/simulations are still based on a flat surface earth model. The purpose of this paper is to quantify the effect of topographic irregularities on the ground motion and local site response by means of parametric investigations in the frequency-domain of typical two-dimensional features.

To this end, we deploy best-practice tools for simulating seismic events in arbitrarily heterogeneous formations; these include: a forward wave simulator based on a hybrid formulation encompassing perfectly-matched-layers (PMLs); unstructured spectral elements for spatial discretization; and the Domain-Reduction-Method that permits placement of the seismic source within the computational domain, thus allowing consideration of realistic seismic scenarios.

Of particular interest to this development is the study of the effects that various idealized topographic features have on the surface motion when compared against the response that is based on a flat-surface assumption. We report the results of parametric studies for various parameters, which show motion amplification that depends, as expected, on the relation between the topographic feature's characteristics and the dominant wavelength. More interestingly, we also report motion de-amplification patterns.

1. Introduction

Understanding and quantifying the seismic response in regions with surface irregularities, such as hills, valleys, and alluvial basins, have been the focus of seismologists and earthquake engineers for decades. The interest remains strong since discrepancies still exist between the recorded surface motion from strong earthquakes and numerical simulations. There are many reasons for the discrepancies, but chief among them are uncertainties about the subsurface properties (velocity model, fault location/geometry, etc.) used in seismic motion simulations, uncertainties in quantifying the seismic source mechanisms, and the lack of adequate representation of topographic features. Empirical evidence following strong earthquakes suggests that topographic features may induce amplification, and even de-amplification, in the proximity of a topographic feature. For example, Fig. 1 depicts damage following the 2010 Haiti earthquake, where buildings closer to the hill's crest suffered more damage than those along the hill's side.

The literature on the effect of surface geometry on wave motion falls into three general categories: (i) observations from earthquakes and field experiments; (ii) studies based on analytical and semi-analytical solutions for simple topographic geometries, such as a triangular wedge or a semi-circular valley; and (iii) parametric studies based on numerical simulations. In the first category, examples include observations in the aftermath of the 1971 San Fernando Valley earthquake [13]; the 1987 Whittier Narrows earthquake [27]; and the 2002 Molise earthquake in Italy [32]. Çelebi [15] investigated the topological amplification of the 1985 Chile earthquake and reported on the damage pattern to structures situated on ridges and soft soil sites. He concluded that the unusual patterns of structural damage resulted from frequency-dependent amplification due to the surface irregularities. Later, in 1991 [16], Çelebi collected and summarized the results of case studies on three earthquakes, and provided evidence of topographic amplification for a particular range of frequencies. Hartzell et al. [23] studied the cause of the structural damage and ground cracking observed at the Robinwood Ridge during the 1989 Loma Prieta earthquake and argued that the presence of ridges intensifies the motion amplification.

Assimaki studied the 1999 Athens earthquake in Greece [5,7] and showed that the observed amplification of seismic motion in the vicinity of a cliff crest could only be predicted by simultaneously accounting for the topographic geometry, stratigraphy, and nonlinearity. The analysis of the Tarzana Hill recordings from the 1987 Whittier Narrows and the 1994 Northridge earthquakes by Graizer [22] showed that the observed amplification was due to the combined effects of

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Fig. 1. Destruction pattern on the hill crest following the 2010 Haiti earthquake.

topography and layering that resulted in trapping energy within a low-velocity layer near the surface. Similar observations were also reported in [42,43,52,53]. Further reviews on observations on seismic amplification can be found in Massa et al. [33], and Buech et al. [14].

Field experiments could also provide insight into the effect topography plays in seismic amplification, but due to cost considerations there have only been a few reported attempts. Buech et al. [14] installed a seismic array along the crest of a hill in New Zealand to record earthquake data. They reported large amplification along the crest, as large as eleven times of the motion on the flat surface. Massa et al. [33] performed a similar experiment using data from a seismic network installed on a ridge in central Italy. They reported amplification as large as 4.5 at specific frequencies. More recently, Wood and Cox [58] exploited ground shaking generated in a coal mine in central Utah and reported significant amplitude changes due to topography. Similar field experiments can also be found in [23,38,40].

Whereas exact solutions of wave motion in a homogeneous, flat-surface, half-space are readily available, closed-form solutions for a half-space exhibiting a surface irregularity, even one described by a canonical shape, are scantier. Among such exact solutions, the greatest attention has been paid to the scattering of SH waves, owing to the scalar form of the associated wave equation. One of the earliest studies is due to Sills [51] where a method was developed to solve the scattering of SH waves by an arbitrary topography in a homogeneous, semi-infinite half-space using an integral equation. Sills applied the method to a semi-circular hill, to a Gaussian hill, and to a combination of a hill and a valley for various wave motion characteristics. Trifunac [55] presented a closed-form solution for the diffraction of SH waves by a semi-cylindrical canyon and reported strong amplification near the feature. Sánchez-Sesma et al. [47] developed a boundary integral method for the scattering of SH waves by any irregular feature. In 1985, Sánchez-Sesma [49] described another method particularly suited for infinite wedge-shaped hills and valleys.

Exact solutions for the vector equation, accounting for P and SV waves in the presence of a surface feature are rare. One exception is the analytical solution proposed by Sánchez-Sesma for an infinite wedge [50]. Paolucci [39] has also provided a simple approximate expression for the fundamental frequency of triangular hills.

In the absence of exact solutions, numerical tools have long been used for simulating wave motion in complex domains. We cite representative works, classified according to the underlying numerical method: (i) finite difference method-based approaches (FDM), which are simple to apply but have difficulties with modeling of the complex surfaces [13,36,37,54], (ii) boundary element-based methods (BEM), which have the advantage of dimensionality reduction, but are limited to cases for which the Green's functions are available. Two major BEM approaches exist, direct (DBEM) and indirect (IBEM). Examples of (DBEM) include the works by Wong and Jennings [57], Álvarez-Rubio et al. [1], Kamalian et al. [24] and, Nguyen and Gatmiri [35], whereas examples of IBEM include the works by Sánchez-Sesma and Campillo [46], Sánchez-Sesma et al. [48], Luzón et al. [31], Gil-Zepeda et al. [20], and Rodríguez-Castellanos et al. [44]. (iii) finite element-based approaches (FEM) which include the works of Moczo et al. [34], Assimaki et al. [6,8], Chaljub et al. [17], Peter et al. [41], and Kucukcoban and Kallivokas [30]. (iv) spectral element-based methods (SEM), that have all the advantages of finite elements, while also allow for easy parallelization. See, for example, Komatitsch and Tromp [28], Komatitsch and Vilotte [29], and Fathi et al. [19].

A few parametric studies conducted so far shed light on the problem of seismic amplification. Ashford and Sitar [2], and Ashford et al. [3] performed a frequency domain parametric study on the effect of single-slope topography on the propagation of shear waves. Assimaki et al. [4,5] 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, stratigraphy, and the geometry of the cliff are all important in the amplification of incoming seismic waves.

Although much work has been done to date, the influence of surface topography is still neglected in seismic code provisions, since the codification of the links between amplification and topographic characteristics remains a challenge.

The main goal of this paper is to contribute to a better understanding of the effects of surface topography on site response by means of a systematic parametric investigation. To this end, we consider parameters such as feature geometry, incident wave type, angle of incidence, Poisson's ratio, and incident wave frequency. In this study, we focus on P and SV waves, and omit SH waves because their effects have already been addressed in the literature. In the following, we first describe the key components of a software toolchain developed for conducting the parametric study. Numerical examples validating the methodology against known solutions appear in Appendix B. The results of the parametric studies involving idealized hills and valleys follow the methodology presentation.

2. Wave motion simulation methodology

We briefly discuss an approach that deploys best-practice tools for simulating seismic events in arbitrarily heterogeneous formations. The approach includes: a forward explicit wave solver based on a hybrid formulation that includes perfectly-matched-layers (PMLs) for limiting the computational domain; the Domain-Reduction-Method that permits placement of seismic sources within the computational domain; unstructured spectral elements for spatial discretization; and parallelizing tools that allow for a scalable and cost-effective numerical simulation of wave propagation.

The use of a domain discretization method (finite or spectral elements) requires that the extent of the semi-infinite physical domain be truncated to form a finite computational domain by introducing appropriate absorbing boundary conditions at the truncation surfaces. To this end, we make use of an unsplit-field Perfectly-Matched-Layer formulation, described in Kucukcoban and Kallivokas [30], and in Fathi et al. [19].

Accordingly, the original semi-infinite physical domain is reduced to a finite domain (Fig. 2), which is further partitioned into the interior computational domain Ω, and the surrounding PML buffer zone. Per [19,30], the formulation leads to the following equations of motion for the discrete problem (in the frequency domain):

$$(-\omega^2\mathbf{M} + i\omega\mathbf{C} + \mathbf{K})\mathbf{d} = \mathbf{f}, \tag{1}$$

where the various matrices and vectors are defined as:

$$\mathbf{M} = \begin{bmatrix} \overline{\mathbf{M}}_{\rm RD} + \overline{\mathbf{M}}_a & \mathbf{0} \\ \mathbf{0} & \mathbf{N}_a \end{bmatrix}, \mathbf{C} = \begin{bmatrix} \overline{\mathbf{M}}_b & \overline{\mathbf{A}}_{eu} \\ -\overline{\mathbf{A}}_{el}^T & \mathbf{N}_b \end{bmatrix}, \mathbf{K} = \begin{bmatrix} \overline{\mathbf{K}}_{\rm RD} + \overline{\mathbf{M}}_c & \overline{\mathbf{A}}_{pu} \\ -\overline{\mathbf{A}}_{pl}^T & \mathbf{N}_c \end{bmatrix},$$

$$\mathbf{d} = [\mathbf{U} \quad \Sigma]^T, \quad \mathbf{f} = [\bar{\mathbf{f}}_{\rm RD} \quad \mathbf{0}]^T. \tag{2}$$

In (1), the subscript RD denotes the regular/physical domain, and