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On the complexity of seismic waves trapped in irregular topographies

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ABSTRACT

Documented observations from strong seismic events have repeatedly shown that the ground surface topography significantly affects the characteristics of seismic waves (amplitude, frequency and duration) travelling from the deeper layers of the crust compared to what the ground motion would have been on the surface of a flat homogeneous linear elastic half-space. Although numerous theoretical studies have qualitatively corroborated these observations, they systematically underestimate the absolute level of topographic amplification up to an order of magnitude or more in some cases. In this paper, we try to bridge the quantitative gap between previous theoretical studies and observations by systematically studying the role of geometry, stratigraphy, and ground motion characteristics through a series of elaborate numerical analyses. We show a collection of examples that highlight the effects of topography on seismic ground shaking, and we point out what these results suggest in the context of the current state of earthquake engineering practice. Examples range from semi-analytical solutions of wave propagation in infinite wedges to three-dimensional numerical simulations of topography effects using digital elevation map-generated models and layered geologic features. We conclude by demonstrating that topography effects vary strongly with the stratigraphy and material properties of the underlying geologic materials, and thus it cannot be accurately predicted by studying the effects of ground surface geometry alone.

1. Introduction

The term local site conditions refers to the mechanical properties of near-surface geological formations and the geometry of the ground surface and subsurface. Local site conditions can significantly distort the seismic waves that travel from the deeper layers of the crust compared to what the ground motion would have been on the surface of a flat homogeneous linear elastic half-space. This distortion that takes place in the near-surface is referred to as 'site effects', and includes phenomena such as large amplification, frequency content shifts and significant spatial variability of seismic ground motion, all of which are very important for the assessment of seismic risk, in microzonation studies, and in the seismic design of important surficial and subterranean facilities.

Although the problem of seismic wave scattering by topographic irregularities has been studied for several decades in seismology and geophysics, only recently it has attracted the attention of geotechnical earthquake engineering researchers. Topography effects are prominent changes of seismic signals (intensity, frequency content and duration) that systematically take place when seismic waves encounter in their path topographic features (hills, ridges, canyons, cliffs, and slopes); subsurface geologic formations (sedimentary basins, alluvial valleys); and geological lateral discontinuities (e.g., ancient faults, debris zones). The effects of the interaction between propagating waves and surface or subsurface irregular geologic features can be dramatic: examples of records that have been attributed in part to topography effects include the PGA = 1.93 g recording of the hilltop Tarzana station during the 1994 Northridge Earthquake [1]; the Pacoima Dam PGA = 1.25 g recording during the 1971 San Fernando earthquake [2]; and the recent extraordinary ground motion PGA = 2.75 g recorded at K-Net station MYG004 on the crest of a 5 m high, steep man-made slope during the 2011 Tohoku Earthquake [3]. Extensive review studies that include numerous other examples have been published by Geli et al. [4], Bard [5], and Assimaki et al. [6].

Observational evidence from past earthquakes indicates that damage concentration occurs where steep slopes or complicated topography are present; buildings located on the top of hills, ridges, and canyons, suffer more intense damage than those located at the base. There is also strong-recorded evidence that surface topography affects the amplitude and frequency content of the ground motions. Reviews of such instrumental studies and their comparison to theoretical results can be found in Geli et al. [4], Faccioli [7], Finn [8] and Bard [5]. Prompted by observational and instrumented evidence, the problem of scattering and diffraction of seismic waves by 2D idealized topographies on the surface of elastic homogeneous half-spaces has been studied by many researchers (e.g. [9–14]). A limited number of studies on complex configurations such as topography with soil layering and/or 3D effects can be found in Bard and Tucker [15], Ashford et al. [16], Graizer [1], Assimaki et al. [17,18] and Assimaki and Jeong [19].

Numerical and semi-analytical published studies have qualitatively corroborated these observations, but when compared to field recordings, have been shown to systematically underestimate the absolute

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level of amplification up to an order of magnitude or more in some cases. This discrepancy between theory and observations has been attributed, at least in part, to idealizations of the above studies such as the assumptions of 2D geometry, homogeneous medium, linear elastic response, and monochromatic or narrowband ground shaking.

In this paper, we provide an overview of our work over the past decade (see, e.g., [20–22]), which has focused on bridging the quantitative gap between theoretical studies and observations by studying the role of geometry, stratigraphy, and ground motion characteristics through a series of high-fidelity, parametric numerical analyses. We start from the topographic amplification caused by a 2D infinite wedge in a homogeneous elastic medium, and we shed new light on the physics of wave focusing and scattering by this fundamental block of irregular ground surface geometry. From there, we gradually increase the geometric and stratigraphic complexity up to a 3D convex layered topographic feature, identifying in each level the controlling factors of ground motion amplification. All simulations are performed for linear elastic materials, appropriate to represent the geologic material response to low strain motions. For the cases that we expect nonlinear large deformation, the results of this study may be considered as improved input motions (demand) that should be later combined with appropriate material properties and constitutive models (capacity) to render a more realistic picture of the site response. In all analyses, we use the Ricker wavelet [23] – a narrowband pulse with a smooth frequency spectrum – as an input motion at the base of model. The dimensionless parameters (height, width, and thickness) that have been used for generic interpretation of the results are obtained by normalizing with respect to the dominant wavelength of input Ricker pulse (at its central frequency). We note that using a more realistic broadband input motion would result in more complex interference patterns and hence produce theoretical seismograms that better match with actual field recordings. However, and for the purpose of this study, a short duration Ricker wavelet with a well-defined spectral content around the central frequency better adapts to control the characteristic parameters of ground shaking, namely, amplitude, frequency and duration. Our results provide new insights into the effects of surface topography and its nonlinear coupling with subsurface soil layering, and suggest that in real conditions, topographic amplification can be quantitatively captured only when geometry and stratigraphy of the site are simultaneously accounted for in theoretical and numerical predictive models.

2. Infinite wedge: first order geometric complexity

Wedge models have been traditionally used in wave propagation studies as fundamental blocks of geometric discontinuities. Typical wedge-shaped features that are of interest in various fields of science and engineering include continental margins, mountain roots, and crustal discontinuities in geophysics and seismology; ground surface topographic features in earthquake engineering; and surface defects and cracks in non-destructive testing.

In seismology and geotechnical earthquake engineering, the solution of wedge problem constitutes an important step towards our understanding of the seismic wave focusing and scattering by wedge-shaped obstacles. When a seismic wave propagates from the source to the ground surface and impings on a wedge-shaped scatterer, its characteristics (e.g. amplitude, frequency and duration) can significantly change because of its interaction with this geometrical heterogeneity. The wedge solution provides physical insight not only in the problem of elastic wave scattering by surface topographies with traction free boundaries but also in dipping layer problems with mixed boundary conditions. In fact, realistic surface and sub-surface topographies can be analyzed – as a first order approximation – as the superposition of simplified convex or concave wedge geometries.

To explain the above premise, consider the initial-boundary value problem of elastic wave scattering by an infinite wedge (Fig. 1). We here simulate the problem using a finite difference (FD) numerical

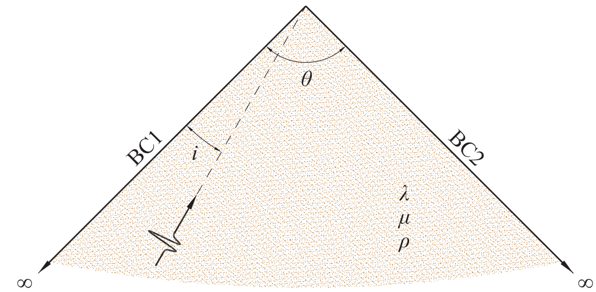

Fig. 1. General configuration of the wedge problem.

scheme, and we validate it for in-plane shear wave amplification at the tip of two wedges ($\theta = 90°$ and $120°$) by comparing our numerical prediction with the analytical solution published by Sanchez-Sesma [12].

For these two scenarios characterized by complete reflection of incident *SV* waves — mode preserving for 90° and mode converting for 120° – Sanchez-Sesma [12] obtained the analytical solution using geometric methods. The numerically calculated velocity time histories at the wedge tip (Fig. 2) show amplification relative to the incident wave amplitude equal to of 6e-4 and 4.0006 for the 90° and 120° wedges, respectively, which –considering numerical rounding errors and resolution – are equal to the corresponding analytical solutions, namely 0 and 4. Fig. 3 shows the seismogram synthetics for these two wedge and wave propagation scenarios, and highlights the path of different wave types. As can be seen, the waveforms consist of the incident *SV* wave (*S*) and its specular reflection from the wedge tip (S_1). The waves *S* and S_1 completely satisfy the boundary conditions along the wedge faces, which is why there is no diffracted wave generated at the vertex.

After validating the numerical model, we extend the solution to a broader range of internal angles. One of the most interesting cases is the vertically propagated *SV* wave incident on the wedge face at the critical angle. For Poisson material ($\nu = 0.25$), the critical angle of incidence and the corresponding wedge angle (critical wedge angle) are 35.26° and 109.48° respectively. Beyond the critical angle, the mode converting part of reflection propagates along the wedge face as a surface wave. This is important for our analysis because the maximum tip amplification occurs at this wedge angle. The scattered wavefield of this geometry is more complex because of additional diffracted *P*, *S* and

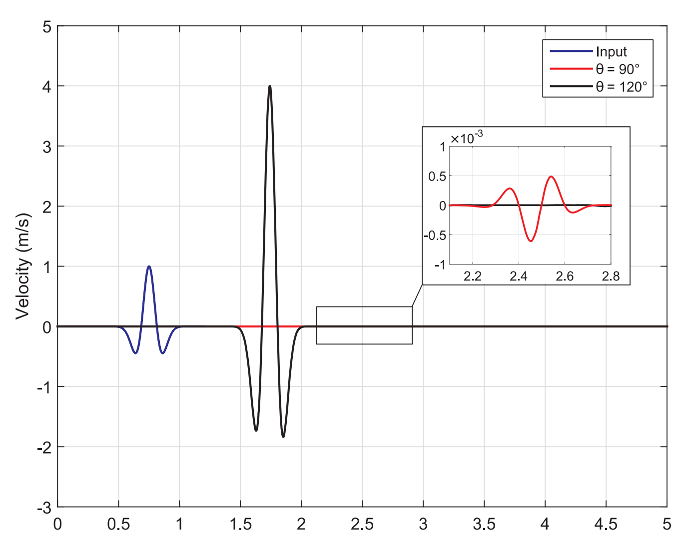

Fig. 2. Velocity time history at the tip – $\theta = 90°$ and $120°$ for an incident ground motion with amplitude 1. Note that the halfspace ($\theta = 180°$) would have amplitude 2.