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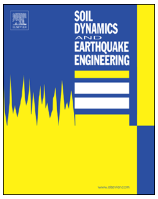

On planar seismic wavefront modeling for estimating rotational ground motions: Case of 2-D SH line-source

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ABSTRACT

At large hypocentral distances, it is convenient to approximate the curved transient seismic wavefronts as planar to estimate rotational ground motions from the single-station recordings of translational ground motions. In this paper, we investigate whether and when this approximation, referred to as the 'plane-wave' approximation, can be considered adequate close to the source. For this, we consider a simplistic source model comprising a two-dimensional, kinematic shear dislocation SH line-source buried in a homogenous, elastic half-space and assume this to be an equivalent representation of a finite-sized fault. The 'plane-wave' rotational motion is then synthesized from the exact translational motion solution to the assumed model and compared with the exact rotational motion solution for this model. The comparison between the two sets of rotational amplitudes in frequency domain suggests that the plane-wave approximation may be adequate, when the wavelengths of the seismic waves are much smaller than the source depth. When this is not true, the plane-wave approximation is seen to underestimate the Fourier amplitudes close to the source by several orders, particularly when the fault planes are vertically oriented. A similar comparison in the time domain indicates that a severe underestimation may also occur when the source rise time is longer than the shear-wave arrival time at the epicenter. Significant discrepancies are also observed between the waveforms of the exact and plane-wave rotational motions.

1. Introduction

Several studies [1–11] have indicated that the rotational components of earthquake ground motions may contribute appreciably to the overall seismic response of civil engineering structures. Observations of large surface rotations in the near-field regions of earthquakes obtained through direct field measurements further strengthen this possibility for the structures located in those regions [12–16]. The paucity of such recordings makes it difficult to characterize the rotational motions and thus construct reliable site-specific rotational design spectra analogous to the conventional design spectra, although some attempts [17–20] have been made in this direction based on approximate estimates of rotational motions. It may take long before a sufficient number of recorded rotational motions become available and therefore in the interim the earthquake engineering profession may have to rely on the theoretical estimates of the rotational accelerations for estimating the seismic behavior of structures to those.

A rotational ground motion is caused by the spatial variation in the translational ground motion as

$$\vec{\Omega} = \frac{1}{2}\left(\vec{\nabla} \times \vec{u}\right) \tag{1}$$

where $\vec{\Omega}$ is the rotational displacement field, $\vec{u}$ is the translational displacement field, and $\vec{\nabla}$ is the curl operator. The spatial variation in $\vec{u}$ results from the phenomenon of wave propagation and is associated with the arrivals of body waves and surface waves at the recording station, though the contribution of the latter may be relatively small close to the source. Since the single-station records of translational motions in such regions are in relative abundance, utilizing those for estimating the corresponding rotational components seems to be a practical approach for getting information on the rotational motion characteristics for those regions. However, it is how $\vec{u}$ varies spatially at the particular recording station (henceforth referred to as the receiver) that we need to know and it has been common to model the spatial variation of translational motion (recorded at a single station) caused by body waves based on the plane-wave hypothesis [21–26].

In the plane-wave hypothesis, the seismic source is treated as being far from the receiver (and hence considered as a point

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source), while the medium is modeled as a homogeneous or horizontally layered, elastic half-space of known composition. Subsequently, each harmonic (frequency) component of the transient motion recorded by the receiver is assumed to result from the planar harmonic wavefronts that are perpendicular to the source-receiver ray. It is further assumed that the harmonic component of the in-plane motion results from the planar wavefront associated with the incident P-and SV-waves (and surface Rayleigh waves), while the harmonic component of the out-of-plane motion results from the planar wavefront associated with the incident SH-wave (and surface Love waves). These three plane-waves, which are defined relative to the source–receiver plane and are associated with a particular frequency, are assumed to be incident at unique angles at the receiver's location. Castellani and Boffi [22,24] based the incidence angles on the source-receiver geometry and subsequently obtained the amplitudes of these plane waves from the translational Fourier amplitudes. Some researchers [25,26] have considered the incidence angles as dependent on frequency, but there does not appear to be a sound physical basis for this assumption. For this reason (and as explained later), this study is focused only on the plane-wave hypothesis as stipulated by Castellani and Boffi [22,24].

Once the amplitudes and incidence angles associated with each incident wave-type are determined [22,24], the corresponding rotational amplitudes can be obtained by using Eq. (1) as shown by Trifunac [27]. Finally, on adding the contributions from all the incident wave-types, the net synthesized rotational ground motion spectrum can be obtained. The plane-wave approach thus offers the convenience of estimating rotational amplitudes at a given site without requiring various often-unknown details of the seismic source. However, this approach may not be applicable within several dimensions of the fault-plane, since the ground motion in this case significantly depends on the geometry of the fault surface and how the slip (dislocation) is distributed on that surface. Furthermore, the seismic wavefronts which are approximated as planar in this approach (referred to as the 'plane-wave approximation') may be 'too curved'. Since no study has so far discussed the adequacy of the plane-wave approach, it will be desirable to know how close to the epicenter the plane-wave approach may be used without introducing significant errors in the estimation of rotational motions.

This study is aimed at the estimation and characterization of the errors in the rotational amplitudes synthesized on the basis of the plane-wave approximation in the regions close to the source. We only investigate the aspects related to the modeling of the wavefronts under the plane-wave hypothesis and for this we compare the exact and plane-wave solutions of rotational motions for a suitable source–medium configuration. It may be noted that depending on the choice of source and how the medium is modeled (single or multilayered), different conclusions would be obtained on the adequacy of the plane-wave approximation. We therefore choose a kinematic dislocation source for this study, since this captures the essential physics of dynamic faulting that is associated with most earthquakes. This model has also been used by many researchers (e.g., [28–35]) to infer the source details, such as fault geometry, slip-distribution, rupture history, of seismic events through various source-inversion techniques that make use of the corresponding near- and/or far-field translational ground motion data. Further, we focus exclusively on the plane-wave approximation associated with SH-waves (which is independent of P-and SV-waves) and model the medium as a homogeneous half-space for simplicity. To further simplify the analysis, we assume that the actual seismic source of finite dimensions can be modeled as an 'equivalent' line-source that produces the same out-of-plane component of ground motion as the recorded one. Thus, the seismic model considered in this study comprises a two-dimensional dislocation line-source buried in a homogeneous half-space medium. This is more convenient than considering a dislocation point-source, since a point-source radiates P-and SV-waves as well. Further, the (cylindrical) transient wavefronts of the line-source retain the curvature in the plane perpendicular to the source-axis, thus making those a reasonably good, first-order approximation of the point-source wavefronts for achieving the objectives of this study. The rotational motion thus obtained (by exactly solving the two-dimensional SH dislocation problem) becomes the actual solution. On the other hand, as mentioned above, the plane-wave solution is obtained as in Castellani and Boffi [22,24] by modeling the wavefronts as planar and by choosing their incidence angles as the angle that the line joining the receiver with its perpendicular projection on the source-axis makes with the normal to the free surface. Considering that none of the SH-waves scatter or undergo internal reflections in a homogeneous medium during their journey from the source to the receiver, this assumption seems to have a better physical basis than the scenarios considered by [25,26].

We first solve the dislocation problem of the chosen seismic source in frequency domain and highlight the nature of differences between the actual and plane-wave rotational spectra in the regions close to the source for variations in various source parameters like SH wavelength, focal depth and dip-angle and medium parameters like shear-wave velocity. We then solve the same problem in time domain for an appropriate choice of the dislocation function characterized by the rise time and compare the peak amplitudes and waveforms of the actual and plane-wave rotational ground motions for variations in the parameters characterizing the dislocation line-source model.

2. Source–medium description

We consider a kinematic shear dislocation source embedded in a homogeneous, isotropic, elastic half-space that is free of body forces. In this model the fault is represented by an internal surface of vanishing thickness across which there is a discontinuity in the displacement resulting in the earthquake. The stresses, on the other hand, are assumed to be continuous on either side of the fault surface. Consequently, for a prescribed spatio-temporal distribution of the slip (kinematic shear dislocation) at the fault surface, the seismic wavefield can be uniquely determined at every point of the medium using the elastodynamic representation theorem. The fault geometry of the seismic source considered in this study is that of a strike-slip fault (see Fig. 1(a)) of infinitesimal width ds and infinite length (along the x_2-axis). The relative slip movement (characterized by the function $D(t)$) at its fault plane is assumed to take place in the right-lateral direction and uniformly and instantaneously (i.e., with infinite rupture velocity) along the entire fault length. This generates cylindrical SH wavefronts, propagating radially outwards from the source axis with the shear-wave velocity β and causing the resulting motion to be invariant with respect to x_2. As mentioned in the introduction, this is a simplistic representation of the rupture initiating from a point on the fault plane and then non-uniformly spreading over the finite rupture area with finite velocity.

Fig. 1(b) shows the plane containing the receiver, taken perpendicular to the source axis. In this figure the source can be considered as a point that generates circular wavefronts. Let the system of $x_1 - x_3$ axes be centered at the epicenter, with the x_1-axis oriented in the epicenter-to-receiver direction and the x_3-axis oriented vertically upwards. The focal depth and fault dip-angle are denoted by h and δ, respectively. The only non-zero translational displacement component in this model is u_2 (along the x_2-axis) and this varies spatially in both the x_1- and x_3-directions. Thus, in general, the non-zero rotational displacements in the