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Estimation of rocking and torsion associated with surface waves extracted from recorded motions

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ABSTRACT

By exploiting the capability of identifying and extracting surface waves existing in a seismic signal, we can proceed to estimate the angular displacement (rotation about the horizontal axis normal to the direction of propagation of the wave; rocking) associated with Rayleigh waves as well as the angular displacement (rotation about the vertical axis; torsion) associated with Love waves.

For a harmonic Rayleigh (Love) wave, rocking (torsion) would be proportional to the harmonic vertical (transverse horizontal) velocity component and inversely proportional to the phase velocity corresponding to the particular frequency of the harmonic wave (a fact that was originally exploited by Newmark (1969) [15] to estimate torsional excitation). Evidently, a reliable estimate of the phase velocity (as a function of frequency) is necessary. As pointed out by Stockwell (2007) [17], because of its absolutely referenced phase information, the S-Transform can be employed in a cross-spectrum analysis in a local manner. Following this suggestion a very reliable estimate of the phase velocity may be obtained from the recordings at two nearby stations, after the dispersed waves have been identified and extracted. Synthesis of the abovementioned harmonic components can provide a reliable estimate of the rocking (torsional) motion induced by an (extracted) Rayleigh (Love) wave.

We apply the proposed angular displacement estimation procedure for two well recorded data sets: (1) the strong motion data generated by an aftershock of the 1999 Chi-Chi, Taiwan earthquake and recorded over the Western Coastal Plain (WCP) of Taiwan, and (2) the strong motion data generated by the 2010 Darfield, New Zealand earthquake and recorded over the Canterbury basin. The former data set is dominated by basin-induced Rayleigh waves while the latter contains primarily Love waves.

1. Introduction

Differential ground motion associated with the propagation of waves can potentially be an important factor in causing earthquake related ground failure and damage to extended structures. Furthermore, the angular displacement components (rocking and torsion) of ground motion may significantly contribute to the response and damage of structures (e.g., [15,11], just to refer to a couple of the pioneering works; rotational ground motion was the subject of a 2009 special issue of the *Bulletin of the Seismological Society of America* (No. 99, 2B)). In earthquake engineering, recognition that angular displacement components of strong motion may contribute significantly to the response of structures started to appear around the 1960's [19]. It was Newmark [15] who first developed a rational basis for determining the torsional earthquake effects in symmetrical buildings arising from a traveling wave propagating with a constant velocity. Hart et al. [8] attributed a large part of the torsional response of high-rise buildings during the 1971 San Fernando, California, earthquake to the rotational components of the ground motion, while Bycroft [3] associated the differential longitudinal motion, responsible for the collapse of bridges during the 1971 San Fernando earthquake and 1978 Miyagi-Ken-Oki, Japan, earthquake with the rotational components of ground motion. Trifunac et al. [20] discussed the distribution of inferred peak surface strains during the 1994 Northridge, CA, earthquake, and attributed the collapse of bridges to longitudinal differential ground motions. The dynamic strain field in the near-fault region of the above earthquake was investigated also by Gomberg [7] who proposed a method for estimating complete time varying strains from commonly available three-component single station seismic data. Finally, Huang [9] reported that large rotational motions, excited by the 1999 Chi-

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Chi, Taiwan earthquake, were inferred from a dense acceleration array near the northern end of the rupture fault where large surface slips along the fault were observed.

Angular displacement components of strong motion always accompany the translational displacement components induced by seismic waves. However, while the latter are measured directly in the field using commercially available sensors (accelerographs), the former are estimated approximately from the translational records, as there are currently no commercially available sensors to measure 'point rotations' (for a brief history of the development of rotation seismographs see [6]). Newmark, in his 1969 seminal paper, started with the 'point rotation' about a vertical axis expressed by space derivatives of displacements (as demanded by continuum mechanics) and eventually expressed it in terms of the ratio of the transverse (to the direction of propagation) component of translational horizontal velocity divided by an 'average' (i.e., independent of frequency) apparent horizontal phase velocity. This type of analysis is exact for plane harmonic waves and can be extended to consider not only rotation about a vertical axis (i.e., torsion) but also rotation about a horizontal axis (i.e., rocking), as demonstrated by Trifunac [18] (see also [21]). More importantly, it provides a single-station procedure to estimate 'point rotations' from common records of translational motion. The key parameter of the procedure is an appropriate selection of the above-mentioned 'average' apparent horizontal phase velocity, say c_{app} . In a ground breaking paper Bouchon and Aki [2] simulated numerically the rupturing of a fault embedded in a layered half-space and computed the field of differential motions (strains) in the region surrounding the rupturing fault. By comparing waveforms of appropriate components of differential motion with appropriate components of translational velocity, these authors confirmed Newmark's [15] result. Furthermore, they were able to estimate appropriate values for the parameter c_{app}. They observed that while in the immediate vicinity of the fault, c_{app} is controlled by the rupture velocity of the fault, elsewhere c_{app} was controlled by the basement rock shear-wave velocity (i.e., the shear-wave velocity of the medium/layer that contains the source) and not by the near-surface velocities. The latter observation is in agreement with results obtained earlier by Luco and Sotiropoulos [12] who demonstrated that the phase velocity of the ground motion produced by a point of shear dislocation, a few kilometers away from the source, is of the order of the shear-wave velocity in the source layer.

The above results and conclusions make very good sense (and are intuitively appealing), as far as body waves are concerned. However, when the discussion focuses on dispersive surface waves, especially those induced by the presence of sedimentary basins, then, the value of the parameter c_{app} is frequency dependent and depends on the structure/stratification/geometry of the sedimentary deposits. Therefore, if a record of translational seismic motion contains both body as well as surface waves then, in order to accurately estimate rotational motions, we must have the capability to separate surface from body waves so as to accurately estimate rotational motions from each set of waves. It should be mentioned that one of the earliest works to consider the potential simultaneous presence of both body and surface waves on recorded motion, and the necessity to treat them separately was Castellani and Boffi [4,5]. Meza-Fajardo et al. [14] have proposed an effective procedure (referred to as 'Normalized Inner Product' procedure or 'NIP' for short) to identify and extract surface waves from a given translational record of ground motion. The procedure is based on the S-Transform [16] and can be used successfully to identify (and subsequently extract) Rayleigh waves (separately retrograde and prograde) as well as Love waves. Once the surface waves have been extracted, they can be processed appropriately to provide estimates of rotational motions (i.e., rocking or torsion).

In the present work we apply the 'NIP' procedure to identify and extract surface waves and, exploiting the absolutely referenced phase information of the S-Transform, we employ it in cross-spectrum analysis in a local manner, as originally proposed by Stockwell [17]. Specifically, by considering two 'sufficiently' close recording stations ('sufficiency' in proximity of the stations is judged by comparing the wavelengths of the signal to be analyzed with the distance of the two stations projected on the direction of propagation of the signal), the cross-correlation of the 'voices' of the S-Transforms at the two stations, for a selected frequency f, can provide the phase difference at that particular frequency f. This phase difference, combined with the distance of the stations, can provide the phase velocity of the signal at frequency f. Thus, after identifying and extracting the surface waves of a recorded motion, we can apply Newmark's [15] approach to estimate rotational motions using the estimates of phase velocities described above.

We apply the proposed angular displacement estimation procedure for two well recorded data sets: (1) the strong motion data generated by an aftershock of the 1999 Chi-Chi, Taiwan earthquake and recorded over the Western Coastal Plain (WCP) of Taiwan, and (2) the strong motion data generated by the 2010 Darfield, New Zealand earthquake and recorded over the Canterbury basin. The former data set is dominated by basin-induced Rayleigh waves while the latter contains primarily Love waves.

2. Time–frequency extraction of love waves using the NIP

In this section we present a procedure to compute the direction of polarization (and consequently the direction of propagation) of Love waves, which does not require the previous computation of the direction of Rayleigh waves. The advantage of this method is that the calculated angle of polarization is not affected by the assumption regarding the type of Rayleigh wave motion which is present in the signal, that is, whether the Rayleigh wave is prograde or retrograde. Furthermore, because the computation of the angle of polarization does not involve the vertical component, the proposed procedure is free of errors that are introduced when the vertical component is of such low amplitude than may be buried in noise.

As in Meza-Fajardo et al. [14] we perform our analysis using time–frequency representations of the components of the signal. We use the Stockwell Transform to map a time-domain component $h(t)$ in the time–frequency domain (τ,f), which is defined in the following form:

$$S(\tau,f)=\int_{-\infty}^{\infty} h(t)\frac{|f|}{\sqrt{2\pi}}\exp\left[-\frac{(\tau-t)^2f^2}{2}\right]\exp\left[-2\pi i f t\right]dt \tag{1}$$

Let us note that since the Stockwell Transform representation of a real function is a complex valued function, with amplitude $A(\tau,f)$ and phase $\Phi(\tau,f)$, it can be expressed as:

$$S(\tau,f)=\mathscr{R}e\left[S(\tau,f)\right]+i\mathscr{I}m\left[S(\tau,f)\right]=A(\tau,f)e^{i\Phi(\tau,f)} \tag{2}$$

In Meza-Fajardo et al. [14] we used the Normalized Inner Product of the vertical and one horizontal component as criterion to identify and extract Rayleigh waves. The NIP can be considered as the time–frequency counterpart of the correlation of signals in the time domain. Thus it can be used to identify and isolate those areas in the (τ,f) domain where the signal components are most (or least) correlated. In the present work we again use the NIP, to extract Love waves, considering only horizontal components. The NIP of two time–frequency components $S_l(\tau,f)$ and $S_m(\tau,f)$ can be