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EFFECTS OF SURFACE WAVES ON THE ROTATIONAL COMPONENTS OF EARTHQUAKE MOTION

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SUMMARY

Rocking and torsion of free surface during earthquakes are proportional to the spatial derivatives of the seismic displacements. These derivatives are inversely proportional to the apparent horizontal velocities of seismic waves involved, and in this respect a remarkable contribution from surface waves may be expected.

A mathematical model of the displacement field around a reference point is here presented, based on an accurate description of the soil layering and an approximate identification of surface waves. The ground motion is assigned at a reference point, and the displacement field is compatible with it.

Rocking response spectra are computed for a historical earthquake, and compared with previously published results. In this example the surface waves contributions are modest in the frequency range of concern for the structural response.

INTRODUCTION

The rotations ψ of the free surface have simple expressions when a proper reference frame is chosen,

$$\psi_x = 0, \qquad \psi_y = \frac{\partial u_z}{\partial x}, \qquad \psi_z = -\frac{1}{2}\frac{\partial u_y}{\partial z} \tag{1}$$

where ψ_y is the rocking about an horizontal y-axis perpendicular to the epicentral direction, ψ_z is the torsion about the vertical axis, z, and the x-axis is taken horizontal and epicenter-site directed. Equations 1 follows from continuum mechanics in the assumption of a stress free surface and indipendence of the motion from the y coordinate [1]. The determination of the rotations thus requires the knowledge of the displacement field in the neighbour of a point.

This problem has received wide attention, and the most fruitful approaches are the strong motion instrument arrays [2,3], the direct simulation of the near-field for a well characterized focal mechanism [4], and some classes of theoretical formulations based on local soil conditions and appropriate assumptions on the wave propagation characteristics [5,6,1].

The present approach pertains to the last cathegory: in a first step, body and surface waves contributions are identified and separated using an approximate technique developed by Sugito et al. [7], then P, SV and SH contributions are deconvolved from body wave contribution using an accurate description of local soil conditions, under restriptive assumptions on body waves path, using a modified formulation of the Thomson-Haskell propagation matrix (see for instance [8]). The displacement field is then expressed as a superposition of plane waves of known direction and wavelength, and rotations of the free surface easily follow.

THE DISPLACEMENT FIELD

Working in the reference system defined above, and assuming that only plane seismic waves, propagating in the x-direction, are present, surface displacements may be expressed through superposition of individual waveforms, characterized by their apparent horizontal velocity, c,

$$\mathbf{u}(t,x) = \textstyle\sum_n \mathbf{u}_n(t - x/c_n) \tag{2}$$

Under wide assuptions, the right member may be expressed as a Fourier integral, giving

$$\mathbf{u}(t,x) = \textstyle\int_{-\infty}^{\infty} \sum_n \mathbf{u}_n(\omega) \exp[i(\omega t - k(\omega)_n x)]\, d\omega \tag{3}$$

with the restriction, for $x = 0$,

$$\textstyle\sum_n \mathbf{u}_n(\omega) = \int_{-\infty}^{\infty} \mathbf{u}(t) \exp(-i\omega t)\, dt = \mathbf{u}(\omega), \qquad \forall\omega \tag{4}$$

The left-member summation may be explicited, for each frequency ω, under the following hypoteses:

- the soil is horizontally layered, each layer is linear elastic, viscously damped and homogeneous;
- the layers rest over a linear elastic, viscously damped, homogeneous half-space (bedrock);
- the earthquake energy is radiated from an immovable point source, located in the bedrock;
- the source is so far that the excitation may be expressed as a superposition of plane waves;
- the body waves propagate in the bedrock on a straight line from source to site;
- only first mode surface waves are relevant in our approximation,

The horizontal wave-number is conserved in reflection and refraction at horizontal layer boundaries, and it is known for body waves propagating on a straight line from source to site, surface waves wavenumbers are also known from soil characteristics, in the assumptions of first mode waves.

The procedure used is detailed in a paper from the authors [9], and is based on the Thomson-Haskell propagation matrix theory.

SEPARATION OF SURFACE WAVES CONTRIBUTION

The identification of surface waves in teleseismic records is based on their arrival time, amplitude and frequency content; surface waves are slower than body waves and arrive later, their pravailing frequencies are lower than body waves frequencies, while their amplitudes are larger, on account of differences in propagation geometry and attenuation characteristics.

The considerations above do not hold true in case of strong-motion accelerograms, recorded at distances up to one hundred kilometers from the source, because the differences in the travel times are of the same order of the energy release duration, and body waves amplitudes are not yet attenuated with distance. As a matter of fact, most strong-motion accelerograms are not suited for an exact recognition of the contributions from different waves, at least if a single accelerometer recorded the event.

The problem may be solved by the method proposed by Sugito et al. [7]: an arrival time and a cut-off frequency are estimated for surface waves from the evolutionary power spectrum of the event, then the accelerogram is filtered, both in time and frequency domain, to separate the surface waves contribution from the remaining part of the excitation, attributed to body waves only.

RESULTS

The method previously described has been applied to provide a measure of the surface rotation for a set of records of the Imperial Valley, California, 10/15/1979 earthquake (the positions of recorders relative to the fault and the record characteristics are summarized in table I). The a_x is here identified with the ±230 component, the positive sign holding for stations laying South-West of the fault (array stations number 12 and 13).

Table I: recording stations

Recording station	Distance from fault	max a_x	max a_z
Array 1	22km	.14g	.05g
Array 12	18km	.12g	.06g
Array 13	22km	.13g	.04g

In particular, the following objectives were pursued:

- a comparison with previously published spectra of surface rotations (Lee and Trifunac [6]);
- a comparison with surface rotations and rotational velocities directly inferred from adjacent instruments records (Niazi [10]);

Given the vertical and horizontal components of the local acceleration, the following steps have been accomplished :

1) development of the evolutionary power spectra and identification of the wave separation parameters;
2) separation of surface wave contributions from the body waves in the acceleration records;
3) separation of P and SV contributions in the accelerations attributed to body waves, using a modified formulation of Thomson-Haskell propagation matrix;
4) syntesis of the rocking acceleration record and evaluation of the rocking acceleration response spectra.

The local layering here assumed coincides with that used in Lee and Trifunac [6] as representative of the Imperial Valley (see table II), and an incidence angle of 0.8 rad for the body waves in the bedrock was used in the analyses.

Table II: parameters of the model of local layering

Layer	depth m	α m/s	β m/s	ρ kg/m^3	ν	ξ %
1	180	1700	980	1280	0.25	6
2	550	1960	1130	1360	0.25	4
3	980	2710	1570	1590	0.25	4
4	1190	3760	2170	1910	0.25	3
5	2680	4690	2710	2190	0.25	3
bedrock		6400	3700	2710	0.25	1

Rocking Spectra Rocking response spectra for the three records under investigation are plotted in fig.1, as well as the rocking response obtained by Lee and Trifunac [6] from an artificial time history. For the sake of a comparison each spectrum has been normalized with respect to a common maximum ground acceleration (vertical component) of $240 cm/s^2$.

Disagreement between the present and the previous research is shown in an intermediate frequency range, due to different assumptions about the wave types involved in the excitation. In the present model the strong motion phase of the records pertain (almost) entirely to body waves of higher apparent velocity, while in Lee and Trifunac the whole excitation is assigned to surface waves.

Velocity and displacement The array station 12 velocity and displacement records have been processed, under the same assumption used for the acceleration records, to provide the rocking velocity and the rocking amplitudes. The results are summarized in table III, in terms of the maxima of the vertical acceleration, velocity and displacement in the second column, and of the rocking acceleration, velocity, amplitude in the third column.

Table III: translational and rocking maxima, array station 12

	translational	rocking
acceleration	$69.95\,cm/s^2$	$7200.0\,\mu rad/s^2$
velocity	$6.92\,cm/s$	$104.4\,\mu rad/s$
displacement	$4.63\,cm$	$30.6\,\mu rad$

Closer to the fault, for the same quantities Niazi [10] has computed the values reported in table IV.

Table IV: translational and rocking maxima, after Niazi [10]

	translational	rocking
velocity	$20.30\,cm/s$	$699.0\,\mu rad/s$
displacement	$12.50\,cm$	$275.0\,\mu rad$

These latter values have been obtained through the elaboration of the experimental data collected by the Imperial Valley differential array during the 10/15/79 earthquake. The distance of the instruments from the fault is about 1km. At similar distances the model here presented is no longer applicable, so that a direct comparison of the above results is not correct, nevertheless these data may suggest a trend of the rocking motion amplitudes with respect with distance from the fault.

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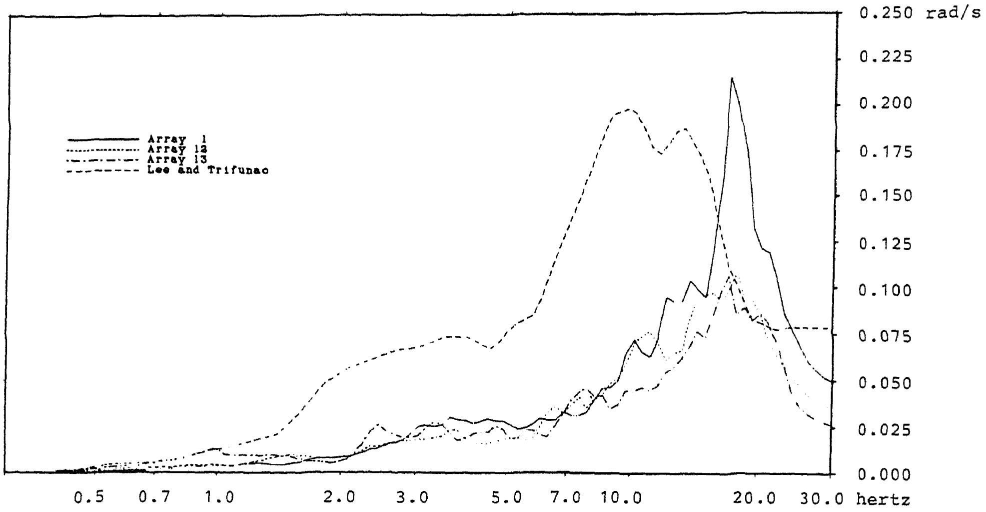

FIGURE 1

Rocking response spectra for the three records under investigation (damping 5%), normalized with respect to a common maximum ground acceleration of 240 cm/s^2, compared with results from Lee and Trifunac [6].