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Characterizing rotational components of earthquake ground motion using a surface distribution method and response of sample structures

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ABSTRACT

Rotational components of strong earthquake ground motion (rocking and torsion) have not been measured directly by instruments deployed in the free field and such components are rarely considered, if at all, in the seismic analysis and design of buildings, bridges, infrastructure and safety-related nuclear structures. The effect of rotational components of ground motion on these structures is therefore unknown. Indirect methods of extracting rotational components from recorded translational data have been developed: a Single Station Procedure (SSP) uses data recorded at one station; and a multiple station procedure (MSP) uses data recorded at a number of closely co-located recording stations (the seismic array). An advantage of MSPs is that site-specific geologic data are not required for the calculations. The Geodetic Method (GM) is a MSP but it cannot retain important high frequencies in the rotational components. The Acceleration Gradient Method (AGM) retains higher frequencies than the GM with the upper limit on frequency being a function of the physical dimensions of the seismic array. A new procedure, the Surface Distribution Method (SDM), is shown to capture high frequencies but some site-specific data are required for the calculations. Results are presented to enable a comparison of SSP, GM, AGM and SDM. The SDM can be used to estimate the three rotational components of ground motion at a reference station across a wide range of frequencies using data recorded in a seismic array. Rotational seismic excitations calculated using the SDM are used to assess their effect on structural response. Three example structures, namely, a chimney, a base-isolated building and the associated fixed-base building are considered. Results indicate that rotational ground motions can significantly affect the response of structures.

1. Introduction

The rotational components of earthquake ground motion have been studied for more than 40 years. However seismic analysis, design and performance assessment of buildings, bridges and safety-related nuclear structures does not address rotational ground motion at this time because such data are not recorded by the accelerographs deployed in the free field and their effects on the response of and damage to structures are unknown. The studies on rotational motions that are of relevance to this paper are summarized below. Basu et al. [3] summarizes other studies on the topic.

Penzien and Watabe [24] enabled the decomposition of three-component acceleration time series into body waves [5]: P, SH and SV. They defined a vertical plane composed of the recording station and the epicenter as the principal plane, and its projection on the horizontal (ground) plane as the principal axis. Penzien and Watabe demonstrated that most of the energy travels to the station on this principal plane and the three components along and normal to the principal plane are uncorrelated. For SH wave reflection from the free surface, the ratio of reflected to incident wave amplitude is independent of the incident angle. This observation, and the assumption of Penzien and Watabe, enable the decomposition. The contribution of the SH wave can be readily identified by rotating the horizontal translational ground motions normal to the principal plane. The P and SV waves contribute to the ground motion along the principal axis and in the vertical direction.

A number of researchers have used the definitions offered by Penzien and Watabe to extract rotational time series from measured translational recordings at a single station, including Trifunac [29], Lee and Trifunac [17], Lee and Trifunac [18], Castellani and Boffi [8], Castellani and Boffi [9], Gomberg [15],

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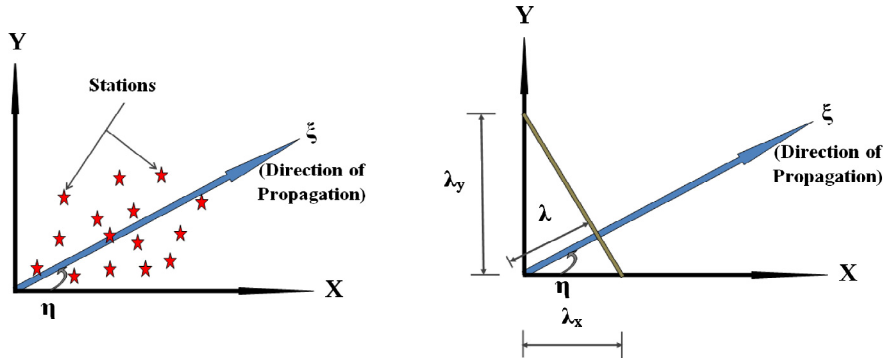

(a) Location of stations and direction of wave propagation

(b) Equivalent wavelength along x- and y- directions

Fig. 1. Wave propagation on horizontal (xy) plane.

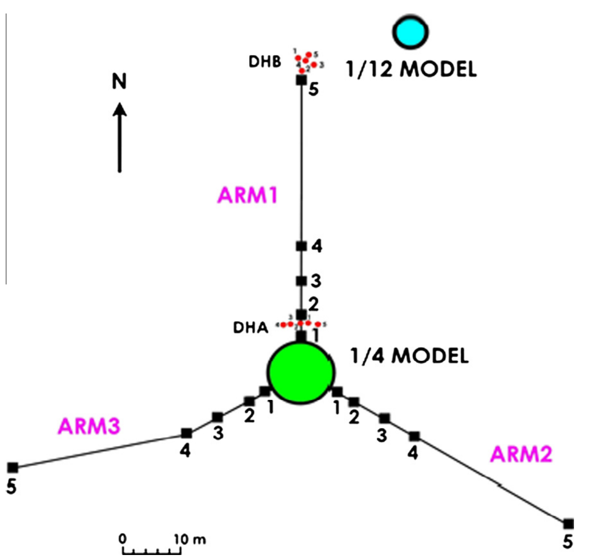

Fig. 2. Station layout in the Lotung array (http://www.earth.sinica.edu.tw/~smdmc/llsst/llsst.htm).

Table 1
Peak translational accelerations and velocities at the surface stations.

Station	Peak translational acceleration (cm/s^2)			Peak translational velocity (cm/s)		
	EW	EW	EW	EW	NS	Vertical
FA1_1	136.5	195.0	132.5	23.4	25.6	4.9
FA1_2	142.1	188.0	115.7	23.1	26.6	5.8
FA1_3	152.0	250.3	107.4	23.1	32.8	7.8
FA1_4	148.2	253.3	105.9	23.4	31.3	6.5
FA1_5	142.3	258.0	104.3	24.2	30.5	5.8
FA2_1	148.1	193.4	92.7	22.0	27.7	8.1
FA2_2	149.6	227.7	96.1	20.9	28.5	7.9
FA2_3	158.7	257.0	141.9	26.0	29.7	5.4
FA2_4	–	–	–	–	–	–
FA2_5	138.9	231.1	82.8	21.8	30.5	5.9
FA3_1	142.5	183.5	118.0	23.0	27.5	8.3
FA3_2	–	–	–	–	–	–
FA3_3	186.9	263.3	127.0	26.6	34.4	6.1
FA3_4	–	–	–	–	–	–
FA3_5	223.1	278.0	212.6	29.8	19.3	5.3

– These stations did not function throughout during the event.

Zembaty [32], Li et al. [19] and Basu et al. [4]. These procedures are described in the remainder of this paper as a Single Station Procedure (SSP). The available single station procedures involve a number of assumptions, including plane wave propagation, existence of a principal plane, lateral homogeneity of the soil medium, a frequency-dependent angle of incidence, the effect of dispersion, and the indeterminacy involved in the deconstruction of the recorded translational time series to contributions from different types of body and surface waves.

An alternative to the single station procedure involves the use of data from a number of closely spaced, spatially distributed stations: the so-called dense array. [In this paper, recording stations close to the center of the array are identified as interior stations; recording stations at the edge of the array are identified as exterior stations.] These multiple station procedures, denoted as MSP herein, have formed the basis of studies to estimate rotational components of ground motion from recorded translational acceleration time series. Niazi [23] estimated rotational motions from the data recorded in a linear array, the El Centro Differential Array (ECDA) in Southern California. The procedure involves fitting a best-fit straight line across the array at every instant of time. The Geodetic Method (GM) of Spudich et al. [28] can be considered as a significant expansion of the work of Niazi. Stations were

Table 2
Apparent wave velocities.

Station	Wave velocity (m/s)			
	Horizontal motion	Vertical motion		
	SH wave (c_{sh})	Recorded	SV wave (c_{sv})	P wave (c_p)
FA1_1	260	1103	189	1231
FA1_2	250	780	176	999
FA1_3	239	836	193	1111
FA1_4	267	783	184	1073
FA1_5	249	715	181	1167
FA2_1	241	1050	196	1291
FA2_2	255	821	198	833
FA2_3	238	1016	182	1181
FA2_4	284	490	220	530
FA2_5	257	558	176	893
FA3_1	230	956	200	1088
FA3_2	237	491	196	866
FA3_3	240	517	180	705
FA3_4	242	419	163	712
FA3_5	241	436	199	591
Mean	249	731	189	951
Standard deviation	14	235	13	239
Coefficient of variation	0.06	0.32	0.07	0.25