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A note on the motion of a large area on ground surface during passage of synthetic strong motion waves

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ABSTRACT

It is shown that the synthetic earthquake displacements over a large area (100×100 m^2) on ground surface can be described well by a plane surface undergoing translations and rotations, with only minor departures of displacements from those of a plane flat surface. Rotational motions are largest on deep soil sites over sediments and smallest for motions on the geological basement rocks.

1. Introduction

During destructive earthquakes, spatial variations of strong ground motion in the near field depend on many factors acting simultaneously (e.g., vibration of blocks, liquefaction, lateral spreading, and landslides; [49,50,52]). In the absence of nonlinear site response, these variations can result from a large pencil of wave arrivals [61], different incidence angles caused by irregular site geology, dispersion of surface waves, and time delays and interference of different waves caused by multiple scattering in three-dimensional irregularities of geologic structure along the wave path and surrounding the site [5,59]. Physically correct characterization of these spatial variations is important for the design of large and long surface and underground structures and for all structures with large plan dimensions in general (nuclear power plants, bridges, and dams) [51].

A comparison of spectral amplitudes recorded in buildings with those outside in the "free-field" shows some filtering effects in the motions recorded on building foundations. These effects have been explained by scattering of incident seismic waves by relatively rigid foundations [15,29,60] and by soil structure-interaction [10,16,26,27]. These filtering effects by large foundations have been argued to be more prominent for buildings with stiff foundation on soft soils [29], but are rarely noticeable for most modern buildings on typical soils in large metropolitan areas (e.g., Los Angeles, California; [21]). This is because the filtering occurs at high frequencies, usually beyond the range included in the frequency range of processed strong-motion accelerograms (i.e., beyond 25 Hz; [36]).

In his paper about the Hollywood Storage Building in Los Angeles, California, Housner [15] erroneously computed the spectral amplitudes that were recorded inside the building, as being smaller than the motions outside, and concluded that large foundations "*iron out the high- frequency components of ground motion*" and that, "*a low, stiff building is benefited by very large dimensions*". The correct processing of the same strong motion records, 44 years later, showed no significant reduction of spectral amplitudes recorded inside the building [21,53]. Nevertheless, Housner's [15], and later Scanlan's [25] papers influenced many engineers to accept the view that large foundations filter out the high-frequency spectral amplitudes of incident ground motions [11,12]. While always present, this filtering is exaggerated by assuming foundations to be rigid. In contrast full-scale experiments show that even for small excitation amplitudes, building foundations deform during the passage of ground waves [17,54,55]. In spite of this observational evidence, in many engineering design analyses an assumed lack of strong-motion spatial coherence at short distances persists, and the wave-propagation effects under large foundations continue to be used to justify the reduction of high-frequency design spectral amplitudes.

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To investigate spatial variations of strong motion, researchers who made early observations used linear arrays of closely spaced accelerographs and occasionally down-hole arrays [30,31,56,6]. With the addition of absolute time to engineering strong-motion instrumentation [8], two-dimensional surface arrays started to be deployed in the early 1970s and have since contributed recordings for analyses and interpretations of spatial variations of strong ground motion [1,28,45]. Early analyses of recorded motions employed cross-correlation functions, response spectra, and Fourier spectra to quantify observed differences in motions at different recording stations. More recently, various forms of coherency, based on power spectral densities, evaluated for a pair of the recording stations, have become a popular measure of the differences between the motions at two points on the ground surface [13,14,22–24].

Ding et al. [9] showed that the distance and frequency dependence of the empirically determined lagged coherences are comparable to those computed from synthetic strong ground motion consisting of body and of dispersed surface waves. Since their method of synthesis (see Appendix A) does not involve attenuation of wave amplitudes by geometric spreading or anelastic attenuation [44,9] results show that the reduction of lagged coherency with frequency and distance is caused mainly by the phase differences of motions at two points. To explore the consequences of these phase differences and how those increase with distance, they calculated motions of a large rectangular area on ground surface (LSA), 100×100 m^2, to find how within this LSA ground surface moves and how it might be distorted by the passage of ground waves. The example they considered was typical for strong ground motion in southern California, and was influenced by the shape of the Fourier amplitude spectra and by the properties of the layered half-space there. Since the lagged coherences also depend on the local geologic and soil site conditions [33], in this paper we extend the results of Ding et al. [9] by examining two additional examples of moving LSA. The results we present confirm that the motions of LSA on layered half-space, in absence of irregular surface and irregular layer geometries, can be described by point translations and rotations only.

2. Motion of a large surface area – LSA

A decrease in the coherency function has been interpreted to imply that the amplitudes of motions at two points separated by some distance d are different. For engineering applications, d rarely exceeds about 100 m and hence following Ding et al. [9], in the following examples we consider again a large surface area (LSA) 100×100 m^2 in plan. Those are rough dimensions of a nuclear island, for example. In the analysis we will orient one of the axes of this LSA along the x coordinate (radial direction that coincides with the direction of wave propagation away from the source, Fig. 1). The second coordinate axis z will be taken positive pointing up, and perpendicular to the horizontal plane of LSA. The motions contributing to the deformations of the radial lines through the LSA will be associated with P and SV body waves and with Rayleigh surface waves. The transverse motions of the LSA, in y direction, will be associated with propagation of SH and Love waves, and will cause torsion about the vertical z axis.

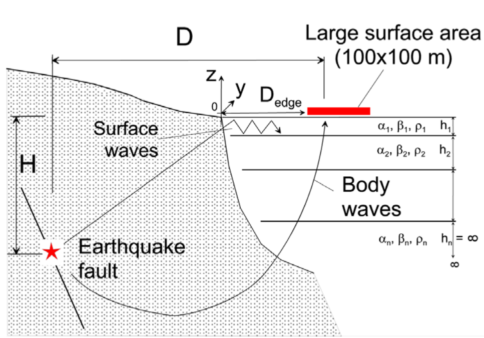

Fig. 1. Schematic representation of a model of earthquake fault, and a segment of the layered structure in the vicinity of the large surface area (LSA).

Our goal is to investigate how the motions of LSA depend on the variables, which describe the incident ground motion (like shape of Fourier and Response spectrum amplitudes), and how these motions depend on the local site conditions. As in the analysis of coherences [9] our results will not be sensitive to attenuation of amplitudes with distance and to the overall amplitudes of strong motion [7]. This is because we will compare motions at small separation distances, less than couple of hundred meters. However, our results will depend on the shape of the Fourier spectra of incident motions, because their shape will determine the relative participation of long vs. short wave lengths of motion, and those will influence the amplitudes of the rotational components of motion [40].

We will illustrate the results by comparison of three examples. In the first example, *E1*, we will consider the shapes of spectral amplitudes of incident strong motion waves, and the site conditions that are representative of areas in southern California [9]. In the second example, *E2*, we will consider a site on geological basement rock (e.g. in a shield area), but will assume the spectral shapes of incident motions to be same as in southern California. In the third example, *E3*, we will again consider the geological rock site conditions (e.g. in a shield area), but will assume that the spectral shape of incident motions is representative of sites in the northeastern America or Canada.

2.1. Example 1 – E1

For this example we use the results previously presented by Ding et al. [9]. They calculated motions of a line along the x axis of LSA (100×100 m^2) for synthetic strong motion computed for $M=6.5$, at epicentral distance $D=20$ km, on sedimentary deposits ($s=0$), at a deep soil site ($S_L=2$), and for probability of exceeding spectral amplitudes equal to $p=0.5$. The calculations of synthetic strong ground motion were carried out by SYNACC computer program ([32]; Appendix A), which assembles contributions to ground motion from body and surface waves, which propagate through a set of parallel layers with finite lateral dimensions. This is illustrated in Fig. 1, in which D is epicentral distance, H is focal depth, D_{edge} is the distance from the edge of the sedimentary basin, and the site (LSA) is located on the surface of a layered half-space. For all examples in this paper we used $D_{edge}=7$ km.

To model the layers of soil and sediments Ding et al. [9] used a site in southern California, which they called *model 3*. The layers at this site have been used also by Todorovska et al [32], and are motivated by a site model used in many previous studies of synthetic calculations of strong motion accelerations and rotations by Lee and Trifunac [19,20] and [47,48], and in the interpretation of

Table 1
Profile for layered cite *model 3* (see [32]).

No.	h (km)	α (km/s)	β (km/s)	ρ (g m/cm³)
1a	0.03	0.4335	0.25	1.2
1b	0.03	0.867	0.50	1.2
1c	0.12	1.70	0.98	1.28
2	0.55	1.96	1.13	1.36
3	0.98	2.71	1.57	1.59
4	1.19	3.76	2.17	1.91
5	2.68	4.69	2.71	2.19