Soil Dynamics and Earthquake Engineering 79 (2015) 253–264

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

journal homepage: www.elsevier.com/locate/soildyn

Coherency of dispersed synthetic earthquake ground motion at small separation distances: Dependence on site conditions

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ARTICLE INFO

Article history:
Received 25 April 2015
Accepted 2 August 2015
Available online 30 October 2015

Keywords:
Coherency of synthetic strong motion body and surface waves
Similarity of strong motion at surface stations less than 100 m apart
Coherency of deterministic dispersed wave

ABSTRACT

Coherency has been used to describe the similarity of strong earthquake ground motion at nearby sites, and for seismic response analyses of structures that are spatially extended, on multiple supports and on large foundations. For that purpose, functions describing its decay with increasing separation distance and frequency are used that have been derived from recorded data by a small number of dense arrays worldwide. Although it has been long recognized that the coherency depends on the site conditions, as demonstrated from comparison of coherencies recorded by arrays with different geology, the recorded data has not been sufficient to study systematically the effects of the site conditions. In this paper, we study the effects of the site conditions using synthetic earthquake ground motion at the ground surface, generated by the SYNACC method. Nine sites are considered, each characterized by a combination of the local soil condition parameter, s_L, and the geologic site parameter, s, and by a corresponding set of parallel layers. Three variations of s_L were considered representing: rock soil, stiff soil, and deep soil, and three variations of s, representing sediments, geological basement rock and intermediate geology. The results show that, for small separation distances (100 m in this case), the incoherence of the ground motion depends on the properties of the layers of soil, sediments and underlying geology. It is shown that the coherency decreases with decreasing stiffness of the soil and rock layers near the ground surface, and with progressively deeper soil deposits. The additional incoherence caused by irregular layer geometry, surface topography and from three-dimensional inhomogeneities beneath the site is not considered in this study.

1. Introduction

The similarity of strong earthquake ground motion at two points in space is commonly expressed in terms of the coherency function, which is also used in engineering applications to compute the seismic response of structures, in particular of structures on multiple supports, such as bridges, as well in soil–structure interaction analyses of large foundations [26,74]. For this purpose, empirical functions describing its dependency on frequency and distance are used that have been derived from data recorded by special arrays with short inter-station distances. Such arrays, however, are only few worldwide, and the relations derived are influenced by the specific geology at these arrays [31,40-42,73,74]. The recorded data is not sufficient to study the dependence of coherency on the local soil and geological site conditions, and the consequences of using the published empirical relations to structures in regions with different geology are not known. In this paper, we attempt to estimate the significance of the site dependency of coherency from a controlled numerical experiment, i.e. in terms of a simple engineering characterization of the site properties, and using synthetic accelerograms. Parallel layers, representing the soil and sediments, characterize the sites we selected and the changes in coherency depend only on the variations in the properties of these layers. Although the commonly used coherency may not be the perfect measure of similarity of ground motion at two points separated by a short distance (in this paper 100 m) for use in earthquake engineering, we adopt it in this study, aiming to examine first what can be learned about this commonly used measure from a controlled experiment.

The synthetic accelerograms are generated using the SYNACC model, in which the site geology for the purpose of describing wave propagation is approximated by parallel layers, while the target Fourier spectrum is defined by empirical equations in terms of a pair of categorical variables, s_L and s, describing the site [48,47,72]. The former, s_L, is the local soil parameter, which

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http://dx.doi.org/10.1016/j.soildyn.2015.08.004
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characterizes the shallow top layers of soil, while the latter, s, is the geological site parameter, which characterizes the deeper geology. These parameters have already been used successfully in many empirical scaling laws for Fourier and Response Spectral amplitudes [54–56,51,59] as well as for duration of strong motion [32–35,37,38]. The parallel layer structure has been chosen to be compatible with the adopted combinations of site categorical variables. The same SYNACC model was used recently to study coherency of strong earthquake ground motion by Ding et al. [7], who showed that a significant portion of the observed loss of coherency at small separation distances (less than 100 m) can be explained to be the result of wave dispersion through horizontal wave-guides. In this paper, we continue their study to investigate how this loss may depend on the soil and geology at the site.

As noted in Ding et al. [7], for large amplitude and destructive strong motion, the causes for coherency variations with small distance are complex and involve many factors acting in unison. Some examples are the focusing of wave energy and nonlinear phenomena (like vibration of blocks, liquefaction, lateral spreading, and landslides; [62,63,65]). For strong ground motion not dominated by nonlinear site response, the spatial variations can be caused by: a broad pencil of wave arrivals associated with large fault dimensions (relative to the source-to-station distance), variations in incidence angles caused by irregular site geology, dispersion of surface waves through nearly horizontal wave guides, and time delays and interference of waves caused by multiple scattering from three-dimensional irregularities in the geologic structure along the wave path and surrounding the site [3,73]. Understanding of these spatial variation and the dependence on the local soil and geologic site conditions is important for the design of long surface and underground structures, and for all structures with large plan dimensions, in general (nuclear power plants, bridges, dams). Their physically correct characterization helps specify representative, site-specific characteristics of the design ground motions for such structures [12–15,17,19,43–45,61,46,58,59,60,64,70,71].

The similarity of recorded earthquake motions at two stations, as measured by coherency, has been found to decrease with increasing frequency and separation distance [1,4,10,11,2,29,30,8,9]. The decrease is small for distances less than about 100 m, but becomes rapid for greater distances. This has been explained by the fact that, for stations that are separated by a small distance, the characteristics of the complete wave paths (from earthquake source to the site) are almost the same, while for stations at larger separation distances they become different [39]. Consequently, for a small separation distance, the drop in similarity is mainly associated with the local site effects, which include the dispersion of surface waves, while, for large separation distances, the effects of different wave paths between the source and the two stations dominate.

In engineering studies, three sources of incoherence are discussed [74]. The first one considers wave scattering, caused by the heterogeneous nature of soil and rock along the propagation paths. The second one is associated with spatial variations due to differences in the arrival times of seismic waves across a foundation and due to inclined wave incidence. In the latter, it is assumed that there is only one apparent phase velocity. The third one, which considers an extended fault surface, is expected to be significant only for small and intermediate fault-to-station distances. For closely spaced stations, the contribution to incoherence from differences in wave attenuation to different stations is expected to be small [6]. In most studies, no other physical models are considered, presumably because of the physical complexities the models would introduce into what appears to be a search for a simplified engineering approach. Yet, the trends that can be extracted from recorded data in more detailed studies suggest that two- and three-dimensional models of soil and site geology must be used [73]. These models can involve the focusing of incident waves by irregular topography and sedimentary basins [27,28], the percentage of time that incident waves spend in sediments vs. basement rock, and the back reflections from the edges of sedimentary basins [59].

The effects of the site conditions have been recognized early on. For example, Schneider et al. [40] compared coherency obtained from data recorded by 10 arrays, five on rock and five on soil sites. They concluded that, at the soil sites, the coherency is smaller than at the rock sites, but less variable among the five arrays on soil sites than the coherency among the five arrays on rock sites. Further, Chiu et al. [5] compared coherencies of motions recorded at the SMART-1 and SMART-2 arrays, both in Taiwan, the latter being located on more consolidated sediments. They concluded that the difference in coherency was not large. More detailed and systematic studies of the effects of the site conditions on coherency have not been possible based on observed data due to the relatively small number of such arrays.

Within the scope of this paper we investigate only the variations of coherency as function of the local soil and geologic site conditions, as incorporated in the SYNACC model. The motion consists of mathematically constructed body and surface waves, in which the wave modes propagate with unchanged amplitudes through a wave-guide. Consequently, the differences in motion at two stations result only from the differences in arrival times of the different modes, which depend on frequency, i.e. from the dispersion. The differences in coherency for different types of site conditions would then be only the consequence of differences in the dispersion characteristics, which result from differences in the layer properties. Results will be presented for horizontal separation distance of 100 m, and for pairs of stations with the same soil and geology. Analysis of cases such that the two stations have different site conditions (e.g. are at opposite sides of a fault, or straddle various topographic or layer discontinuities, as in Lee et al. [27,28], for example) are beyond the scope of this paper.

2. Methodology

The coherency of acceleration for a pairs of stations (j,k), $\bar{\gamma}_{jk}(f)$, is defined as the ratio

$$\bar{\gamma}_{jk}(f) = \frac{\bar{S}_{jk}(f)}{\sqrt{\bar{S}_j(f)\bar{S}_k(f)}} \tag{1}$$

where $S_j(f)$ and $S_k(f)$ are the auto-power spectra (magnitude of the Fourier transform, squared) and $S_{jk}(f)$ is the cross-power spectrum (product of the two Fourier transforms) of the two accelerograms, and the bar indicates smoothing [74]. The coherency is a complex valued quantity, and can be expressed in terms of its magnitude $\left|\bar{\gamma}_{jk}(f)\right|$, termed *lagged coherency*, and phase angle $\bar{\varphi}_{jk}(f)$, termed *smoothed phase spectrum*

$$\bar{\gamma}_{jk}(f) = \left|\bar{\gamma}_{jk}(f)\right| \exp\left[i\bar{\varphi}_{jk}(f)\right] \tag{2}$$

Its real part, $\mathrm{Re}[\bar{\gamma}_{jk}(f)]$, is referred to as the *unlagged coherency*. The lagged coherency has values $0 \le \left|\bar{\gamma}_{jk}(f)\right| \le 1$. However, if $S_j(f)$, $S_k(f)$ and $S_{jk}(f)$ are not smoothed, then $\left|\gamma_{jk}(f)\right| \equiv 1$ for all f, and the coherency cannot express any level of dissimilarity of the motions. The smoothing, therefore, is an essential part of the definition. Many smoothing windows have been used, such as rectangular Bartlett, Tukey, Parzen, Hanning, and Hamming windows. Different types of smoothing windows yield similar results as long as the bandwidth of the windows is the same [16].