# THE SPATIAL VARIABILITY OF GROUND MOTION AND ITS EFFECTS ON MULTI-SUPPORTED STRUCTURES

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**ABSTRACT:**

Observations have shown significant incoherence in earthquake ground motions measured at different locations within the spatial dimensions of large horizontally expanded structures. In Eurocode 8, the effects of incoherent ground motions are addressed, but without the detailing needed for practical applications in engineering design. The objective of this paper is to present a simplified model for design purposes to account for the spatial variability of ground motions. Strong-motion effects measured at different locations within the dimensions of an engineered structure are typically different, even for structures of moderate size. However, the current engineering practice assumes routinely that the excitations at all support points are the same or that they differ only by a wave propagation time delay, i.e., excitations at all locations are assumed to be fully coherent. These assumptions ignore the natural incoherence in the ground motion, which may lead to incorrect or inaccurate results. An improved model should include the main effects governing the spatial structure of strong ground motion i.e. wave passage effects, incoherence effects and local site effects. This study emphasises the horizontal incoherence of ground motion. Selected records from shallow strike-slip earthquakes obtained at rock sites in events with magnitude 6.5 are used to facilitate the study. The horizontal components of the records are transformed into principal coordinates and coherence estimates computed from the strong motion phase of acceleration containing 90% of the wave energy. It is seen that the loss in coherence increases on the average with increasing frequency and increasing separation distance, which is in accordance with results reported in the literature. The presented model is found to be applicable in response calculations of horizontal structures.

**KEYWORDS:** Incoherence, spatial variability, ground motion, Eurocode 8, long structures.

## 1. INTRODUCTION

Observations from closely-spaced strong-motion arrays have shown that earthquake ground accelerograms measured at different locations within the dimensions of typical large engineered structures are significantly different. This has led to considerable research on modelling spatially varying earthquake ground motion and on determining its effect on the seismic response of large horizontal structures. Modifications of the common engineering methods have subsequently been developed to include the effect of incoherent ground motion. Furthermore, in current and upcoming code provisions, i.e. Eurocode 8, these effects are addressed, however, without the sufficient detailing needed for practical applications in engineering design (Eurocode 8, 2003). In order to provide additional information for engineering design, we present in the following a model describing the spatial variability of strong ground motion accounting for the incoherency of wave motion. It should be noted that the model is developed considering limited date from the South-Iceland seismic zone (Sigbjornsson and Olafsson, 2004).

## 2. MODELLING SPATIAL VARIABILITY

Strong-motion effects measured at different locations within the dimensions of an engineered structure are as a rule different, even if the structure is of moderate size. In spite of the similarities, there are some characteristic differences that increase with increasing separation distance. For larger separations the differences become visually quite noticeable and the motion appears uncorrelated. However, the current engineering practice assumes routinely:

a) Excitations at all support points are the same; or
b) Excitations are different by only a wave propagation time delay, i.e., excitations at all locations are taken to be fully coherent.

The first approximation, (a), is acceptable for structures with small horizontal dimensions at the structure-ground interface. The second approximation, (b), is commonly assumed valid for horizontal structures with large dimensions. However, this approach is oversimplified as the incoherence in ground motion is missing, which may lead to incorrect or inaccurate results. Zerva (1994), found the most important effect of the spatial incoherence to be the introduction of significant quasi-static internal forces in the structures.

An improved model should include all main effects governing the spatial structure of strong ground motion (Der Kiureghian, 1996). These can be summarised as follows:

- Wave passage effect: The wave passage effects are resulting from seismic waves arriving at different times at different stations.
- Incoherence effect: The incoherence effects result in loss in coherence of the wave motion. They are due to differences in the manner of superposition of waves (a) arriving from an extended finite source, and (b) wave scattering by irregularities and inhomogeneities along the wave path and at the site.
- Local site effect: Differences in local soil conditions at each station may alter the amplitude and frequency content of the bedrock motions significantly.

Based on these simplified observations, if local site effects are neglected, spatial variability of strong ground motion can be modelled as a locally homogeneous and stationary random field with cross-spectral density given as:

$$S_{rs}(f,d_{rs}) = S_r(f)coh_{rs}(f,d_{rs})\exp(i\phi_{rs}(f,d_{rs})) \quad (2.1)$$

Here, $f$ is frequency, $d_{rs}$ is the separation distance between the observation points referred to by the indices $r$ and $s$, $S_r$ is the auto-spectral density, $coh_{rs}$ is the coherence spectrum and $\phi_{rs}$ is the phase spectrum. By definition $coh_{rs}$ is in the range 0 to 1. Furthermore, we see that the wave passage effects are furnished in the phase spectrum. By inspecting the above equation we see that the coherence spectrum accounts for incoherence, i.e.

loss in coherence visualised by coherence values that are less than one.

Many different models have been suggested for these spectra (Zerva and Zervas, 2002), as such models are required for any practical application of Eqn. (2.1) (Harichandran et al., 1996; Chen and Harichandran, 2001; Lou and Zerva, 2005). In the following we will discuss the coherence and the phase in some details. Regarding the auto-spectral density it is most convenient, in the current case, to derive it from a Fourier representation of the source spectrum (Morikawa et al., 2002).

## 3. COHERENCE

To facilitate this study of horizontal incoherence of ground motion, acceleration records have been selected from shallow strike-slip earthquakes recorded at rock sites in events with magnitude about 6.5. The records were obtained from the ISESD databank (Ambraseys et al., 2004) from sites in South Iceland and in Turkey near the North Anatolian Fault. The records were supplemented by EERC data.

The estimates of the coherence were computed from the strong motion phase of acceleration containing 90% of the wave energy. Then, before carrying out the computations the horizontal components of the records were transformed into principal coordinates. The spectral estimates were obtained using Welch's averaged periodogram method. The sample frequency of the applied records was 100 Hz. The periodograms were obtained using no-overlapping 256 points and a Hanning window of the same length. The resulting estimates of the coherence spectrum is summarised in Figure 1 below, both the results of the Well's approach and estimates obtained using moving average 5-point spectral window. We see that the loss in coherence increases on the average with increasing frequency and increasing separation distance which is in accordance with results reported in the literature.

It is found that an empirical coherence model of the following type, commonly referred to in the literature, does not fit very well to the applied dataset:

$$coh_{rs}(f, d_{rs}) = \exp(-a_1 f)\exp(-a_2 d_{rs}) \tag{3.1}$$

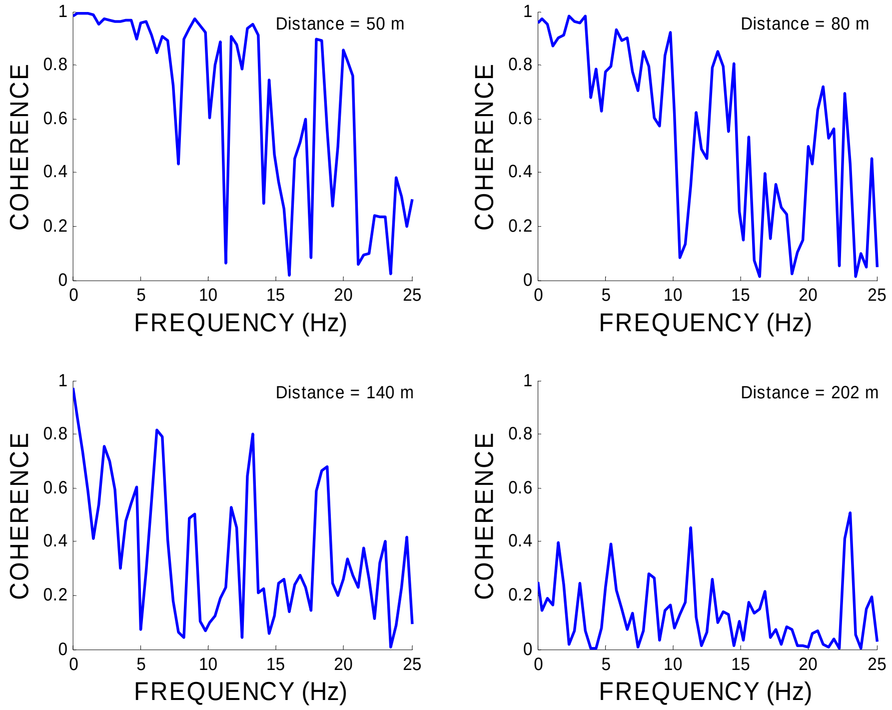
Here $f$ is frequency in Hz, $d_{rs}$ is the separation distance between the observation points in m, $a_1$ and $a_2$ are parameters determined using linear regression analysis. The same applies to the widely referred model by Anderson et al. (1991). An extension of the above model is the following simplified exponential type model:

$$coh_{rs}(f, d_{rs}) = \exp\left(-a_1 f^{a_3}\right)\exp\left(-a_2 d_{rs}^{a_4}\right) \tag{3.2}$$

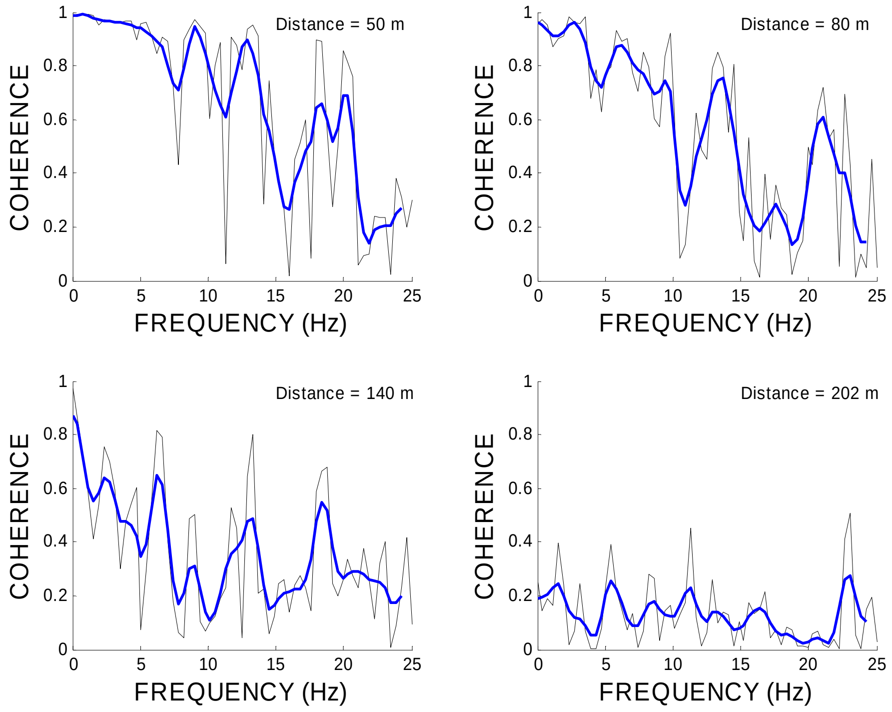
where $f$ is frequency in Hz as above, $d_{rs}$ is the separation distance between the observation points in m and $a_1 \ldots a_4$ are parameters determined using non-linear regression analysis. It should be noted that values of the parameters $a_1 \ldots a_4$ depend on the units used for the frequency and distance. The following values were obtained using non-linear least-squares data fitting:

$$a = [\, a_1 \quad a_2 \quad a_3 \quad a_4 \,] = [\, 3.6462 \cdot 10^3 \quad 0.4890 \cdot 10^6 \quad 1.85 \quad 2.85 \,] \tag{3.3}$$

The results are displayed in Figure 2. The fit is found reasonable with the residual errors normally distributed according to the Jarque-Bera parametric hypothesis test of composite normality (see Figure 3). It is worth noting that the parameters are dimensional dependent.




(a)




(b)

Figure 1 Estimated horizontal coherence spectra. (a) Derived applying Welch's averaged periodogram method. (b) derived using moving average 5-point spectral window (blue curves), the black curves are the same as in Figure 1(a) above.

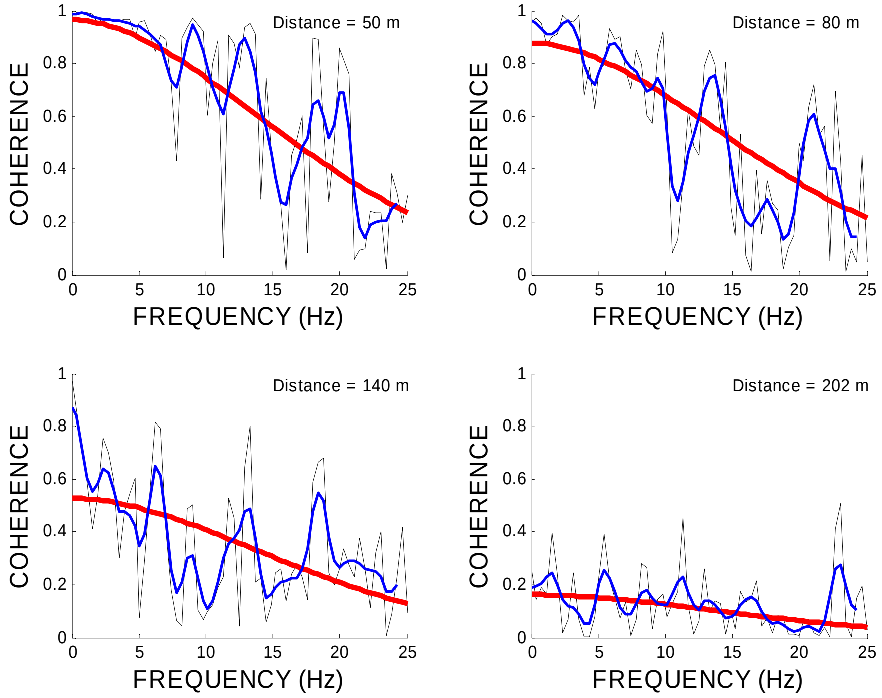



Figure 2 Horizontal coherence as a function of frequency for different distances between observation stations. The black and blue curves are estimates derived from measurements (see Figure 1) and the red curves are simplified fitted exponential type model, Eqn's. (3.2) and (3.3).

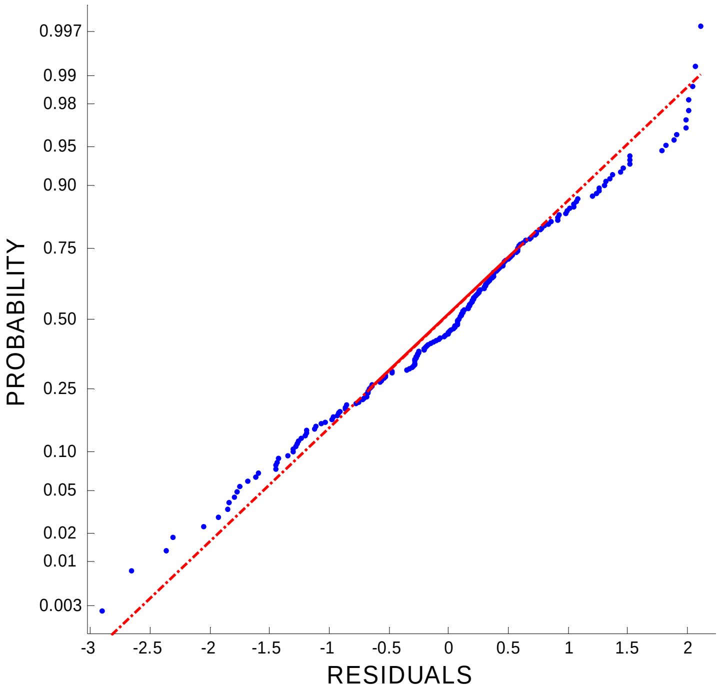



Figure 3 Distribution of residuals derived using the simplified exponential model (see Figure 2). The residuals are given in terms of number of standard deviations. The standard deviation of the residuals is equal to 0.22.

Figure 4 displays three empirical models that have been commonly applied in the literature, i.e. Anderson et al. (1991), Novak and Suen (1987) and Harichandran and Vanmarcke (1986). These models are compared to the data set applied and the suggested model in Eqn. (3.2) for spectral coherency. It is seen that the fit of these models to the applied data varies depending on the spatial distance studied and the frequency of motion. The Anderson model tends to fit the lower bound of the data and thereby underestimate the coherence to some degree. The model of Harichandran and Vanmarke similarly underestimates the coherence of the current data set except for low frequency motion and long spatial separation where it is seen to overestimate the coherence. The Novak and Suen model, on the other hand, overestimates the coherence in current data set for all frequencies of motion. Hence, it can be stated that models found in the literature should always be treated with some caution and tested if reliable data is available. The herein proposed model of Eqn. (3.2) seems to fit the smoothed coherence spectra quite well.

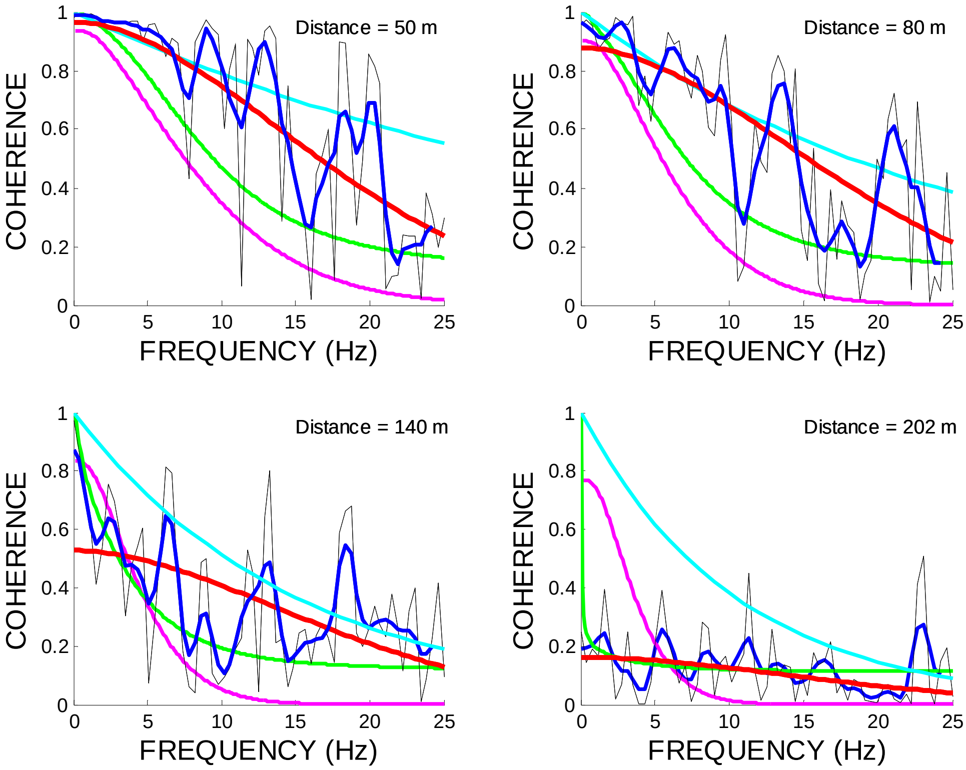



Figure 4 Horizontal coherence spectra. The black and blue curves are estimates derived from measurements (see Figure 1), the green curves are the model of Anderson et al. (1991), the cyan curves are the model reported by Novak and Suen (1987), the violet curve is the model reported by Harichandran and Vanmarcke (1986) and the red curves represents the suggested model in Eqn. (3.2).

The fitted coherence model is displayed in Figure 5. In spite of some theoretical shortcomings this model is found to be a reasonable approximation that fits the selected data better that other available model tested. In this context it is worth noting that the selected data are partly originating from the South Iceland Lowland. Hence, the presented model is recommended for the current study area.

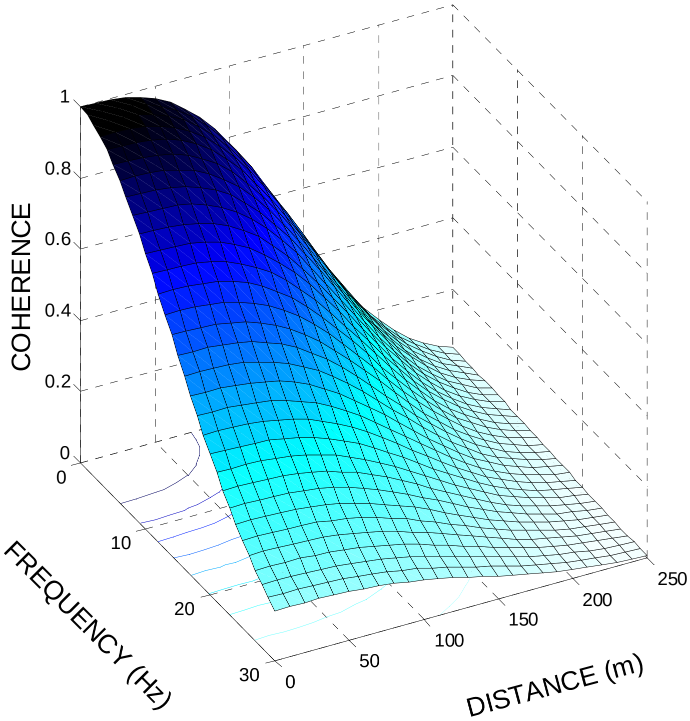



Figure 5 Simplified exponential model for horizontal coherence spectrum expressed as a function of frequency in Hz and separation distance in m. The model used is given in Eqn. (3.2) with the parameters in Eqn. (3.3).

## 4. PHASE

A commonly used model for the phase spectrum is to take it proportional to the gross propagation time delay reflecting the wave passage effects. Along these lines, we suggest the following simplified model for the phase spectrum:

$$\phi_{rs}(f, d_{rs}) = -2\pi \frac{V}{|V|^2} d_{rs} \tag{4.1}$$

Here, V denotes the gross apparent velocity vector and $d_{rs}$ is the separation between observation points. The velocity vector should be transform into principal coordinates before applying this equation with the coherence model outlines above.

## 4. DISCUSSION

The above presented models of Eqn. (3.2) and Eqn. (4.1) are found to represent the data studied quite well. They have been found useful in response calculations of long horizontal structures, especially if linear statistical models apply. For non-linear response cases the above models have found application in simulation of time series.

The coherence model fits the current data considerably better than the three comparative models which have commonly been applied in the literature. The fit of these models to the applied data is found to vary depending on the frequency of motion and the spatial distance studied. It can be stated that models found in the literature should be treated with some caution and preferably tested if reliable data is available.

Further work will include comparison of earthquake response applying the various assumptions and models presented herein.

## ACKNOWLEDGEMENTS

The presented work was supported by Landsvirkjun and the University of Iceland Research Fund.

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