SPATIALLY VARIABLE GROUND MOTION MODELS FOR THE EARTHQUAKE DESIGN OF BRIDGES AND OTHER EXTENDED STRUCTURES

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SUMMARY

This paper presents an empirical model of the spatial variability of ground motion suitable to the design of bridges and other extended structures. The quantification of the model is done with the help of the space correlation function which, however, need not been known but for some of his properties.

Although the model is mainly formulated in terms of a stochastic process idealization of the ground vibration, the use of the model is exemplified considering also time-series of accelerations and response spectra.

INTRODUCTION

The earthquake damage of bridges have been recently a subject of some interest (Ref. 1). The analytical study of the seismic problems of bridges envolves two types of models, viz a model for the structure and a model for the action. When the bridge is longer than about 100 m the motion cannot be considered uniform along the base (Ref. 2) a fact which was found to increase in some cases the severity of the shaking (Ref. 3). Although excellent models are available since some years (Ref. 4 and 5), they are somewhat clumsy for design purposes. This paper present a model which was develloped in order that a deformable base analysis would not be significatively more expensive than a rigid base analysis; it was also endeavored to have a model which could be quantified without difficult to obtain information. For the sake of generality the model was develloped in terms of a stochastic process idealization; the respective response spectra and time series of acceleration versions are easily obtained. Although the model was develloped for bridges it can be applied to the study of earth dams, industrial halls, pipe lines and other extended structures.

THE SPATIAL VARIABILITY MODEL

The model for the spatial variability of the ground motion is develloped from a reference model for the motion at a point. It will be assumed that this motion will be idealized by a non-stationary process obtained by the superposition of time-segments of several elementary stationary Gaussian processes, whose frequency content is determined by their power spectral density function (Ref. 6 and 7). However the spatial variability model is not limited to this particular model of the one point motion, which is only chosen because it is sufficiently general for almost any purpose.

The elaboration of the spatial variability model follows the following rules:

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A) The spatial variability is equal for all components of the ground motion.

B) The power spectral density functions are divided into frequency bands. The highest frequency of each band shall not exceed three times the lowest frequency. In practice, to minimize computations, the limit frequencies are chosen as a geometric progressions of reason three.

C) For each frequency band, a square mesh is defined. The size of the sides of the squares is taken equal to the wavelength corresponding to the lowest frequency of the band being considered. This wavelength should be computed from the mean S-wave velocity for the zone within one or two times the length of the bridge. When the size of the sides of the squares are greater than five times the length of the bridge, the motion is idealized as a rigid base motion and no further banding in the low frequency zone of the spectrum is necessary.

D) The motion at each node of the mesh is stochasticly independent of the motion of the other nodes.

E) The motion of the points on the sides of and inside the squares are obtained by a weighted average of the motion of their four angles.The weighting factor for the motion at an angle is given by

$$\cos\left(\frac{\Pi y_1}{2\ell}\right)\cos\left(\frac{\Pi y_2}{2\ell}\right)$$

where ℓ is the size of the side, and y_1 and y_2 are the coordinates of the point under consideration for a coordinate system whose axes are directed as the mesh and the origin coincides with the angle.

Rule A) is based on that the same natural causes are at work for all the components of the ground motion, at least for the conditions and within the accuracy sought for this model. Rules B), C) and D) define the maximum distance at which the auto-correlation functions is not zero. This distance, for each frequency is comprised between two and six wavelengths, depending on its relation to the band limits and on the particular pair of points being considered (remark that the node points are singular in this respect). The use of wave - length as a gauge to formulate this condition steems from the assumption that spatial variability phenomena should be homogeneous, i.e., what happens for a given frequency band is simillar, at a given scale, to what happens at another frequency band. The values of two to six wavelengths are, of course, arbitrary but were choosen on the basis of the spatial correlations between values of acceleration (Ref. 2) and displacements (Ref. 8); they also not seem unappropriate considering the influence of scattering along the wave path and the reasonable devellopment to be expected of a wave front. The stochastic independence of the motion at each node is also to ease the computation of the response (which is described in Ref. 7 and 9). Rule E) assures that the intensity of the shaking motion is the same everywhere.

As is to be expected from an empirical model, it is to be used only if proeminent site particularities are absent, namely regular strata of significative dimension or well develloped topographical accidents. It is also necessary to acknowledge that,although wavelengths are present in the quantification of the model, it does not incorporate the phenomena associated to wave propagation. Spatial variations of the soil profiles can be taken in account as, for each frequency band, power spectral density functions may change from node to node; this in particular means that soil profiles may influence more the high frequency range than the low frequency range.

USE OF RESPONSE SPECTRA

The spatial variability model also applies if the earthquake motion is defined by a response spectrum. It is then possible to find the equivalent power spectral density function, (Ref. 10), divide it into the different frequency bands and compute the several response spectra corresponding to each band. The response due to the response spectra for each frequency band and for each node are combined by the rule of the "square root of the sum of the squares". Parametric studies under way indicate that no great errors arise if the response spectra themselves are divided into frequency bands and a zero value is assumed for the response spectra of a band outside the limit frequencies of its band (of course, the response spectra of a band tends, for low and high frequencies respectively, for the peak value of displacement and acceleration of the motion corresponding to that band).

USE OF TIME SERIES

It is possible to express the spatial variability model in terms of time series of acceleration; it suffices to start from the stochastic model and generate the corresponding samples. If the stochastic model is stationary Gaussian the generation process is well-known; if, as assumed, it is a superposition of time-segments of several elementary stationary Gaussian processes, it is necessary to apply a more develloped algorithm that have been presented elsewhere (Ref. 7). To exemplify the elaboration of the spatial variation model and show its power an idealized situation will be considered:

Motions are to be generated corresponding to points 100 m apart for a length of 1000 m; wave velocity is assumed as 1000 m/s; earthquake motion is taken as the type 1 action for soil condition type II of the new Portuguese Code (Ref. 11), which is defined by a power spectrum.

The first step is to define motion at a point. If it is whished to use a stationary model the earthquake action definition of the Portuguese Code is sufficient. However, to generate non-stationary time-series, it is possible to compute the response spectra directly from the power spectrum (Ref. 10). The response spectrum for the 5% percentual damping is then used as a reference to calibrate the non-stationary model. The non-stationary model is defined through the power spectral density functions of each elementary stationary Gaussian process and the time interval at which they exist. In this example five elementary processes are considered. The first two model the increasing intensity phase of the earthquake and have a duration of two seconds each. The third elementary process corresponds to the stationary phase and has a duration of six seconds. The decreasing intensity phase of the earthquake is modeled by the fourth and fifth elementary process with durations of seven and thirteen seconds. The elementary processes are justaposed so that the total duration of the time-series is thirty seconds. The frequency content of each elementary process is chosen so as to have an earthquake-like time variation of intensity and frequency content; this choice is assessed through the values of the variance and of the mean frequency of ascending zeros for displacement, velocity and acceleration. The power spectral densities of each elementary process are finally corrected (by a common factor at each frequency) in order that the earthquake model have the reference response spectrum (Ref. 7).

Once defined the model for the motion at a point, the elaboration of the spatial variability model may start. In this case five frequency bands were considered: 0:0.333Hz,0.333: 1Hz, 1:3Hz, 3:9Hz and 9:20Hz (the earthquake action model has no frequency content above 20Hz). Only a linear situation is considered as the bridge is whitout curvature in plan: so the mesh reduces to a straight line. For the 0:0.333Hz frequency band, the base motion is assumed rigid and the weighting function is therefore constant. For the other frequency bands the weighting functions are shown in figure 1. For the 0.333:1Hz frequency band there are three weighting functions as well as for the 1:3Hz frequency band. The 3:9Hz and 9:20Hz frequency bands need five and eleven weighting functions. Each weighting function is identified by a letter and the number of its frequency band, as shown. One, three, three, five and eleven samples were generated for the five non-stationary processes obtained by limiting the frequency content of the non-stationary process model of the motion at a point to the five frequency bands. These samples were then combined according to the weighting functions. For example, motion at 100 m from the origin is obtained by

A1+0.208 A2+0.978 B2+0.588 A3+0.809 B3+0.311 A4+0.950 B4+0.812 B5+0.583 C5

where A1 stands for the sample corresponding to the 0:0.333Hz frequency band, A2 and B2 for samples corresponding to the 0.333:1Hz frequency band, etc...

The time series of acceleration, velocity and displacement (the latter obtained by step-by-step integration of the first) for the eleven points 100 m apart are shown in figures 2,3 and 4. It is interesting to note that the accelerations time-histories are different from motion to motion although similar features are not difficult to find between nearby motions. When considering the velocity time-histories the situation is inverse: the velocities seem identical but it is not difficult to find the evolution of the details from time-history to time-history. The displacements at the different points are almost equal. To emphasize this characteristic they were all plotted in the same axis; thus they appear as a single line with variable width, corresponding the instants in which the line is widest to those instants when there is larger differences between the displacements of the different points. As accelerations, velocities and displacements are associated to high, medium and low frequencies, respectively, the different variability, from point to point, of the histories of acceleration, velocity and displacement illustrates the zeroing of the correlation function for small distances in the high frequency range, for medium distances in the medium frequency range and for large distances in the low frequency range. Response spectra also show this evolution of the correlation between motion at different points. In figures 5 and 6 are plotted the 2% and 5% response spectrum for the eleven earthquake motions. In the low frequency range all the spectra are nearly equal, in the high frequency the spectra are apparently independent (but all with the same severity). In the medium frequency range, as the period increases, the different spectra began to coalesce, presenting increasingly smaller and ordered oscillations.

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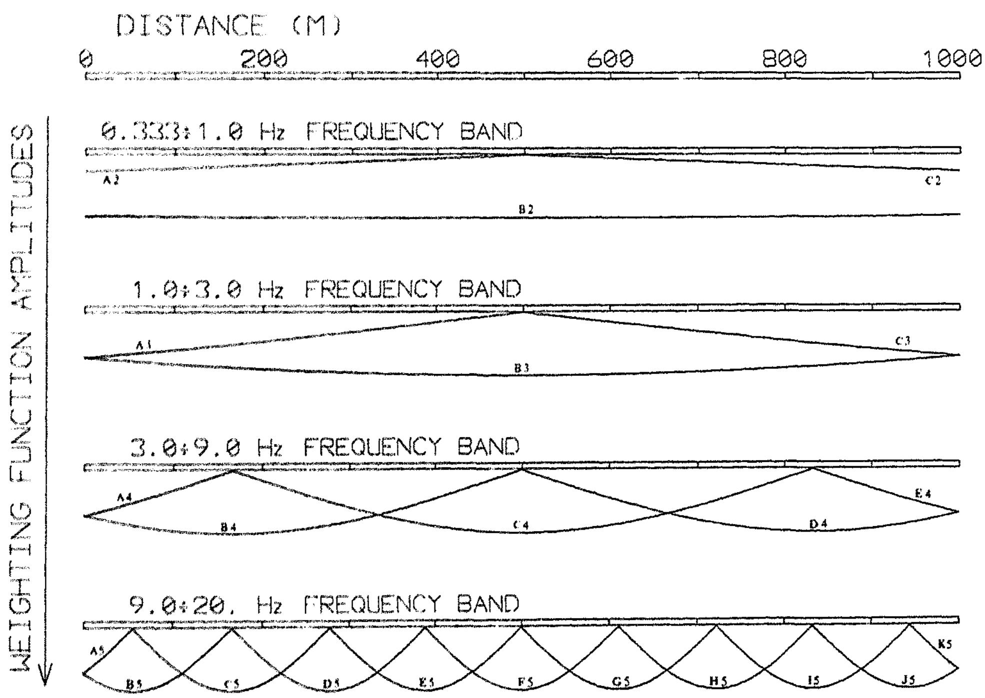

Fig. 1 - Weighting functions for a linear case (the weighting function for the rigid body motion frequency band is not represented).

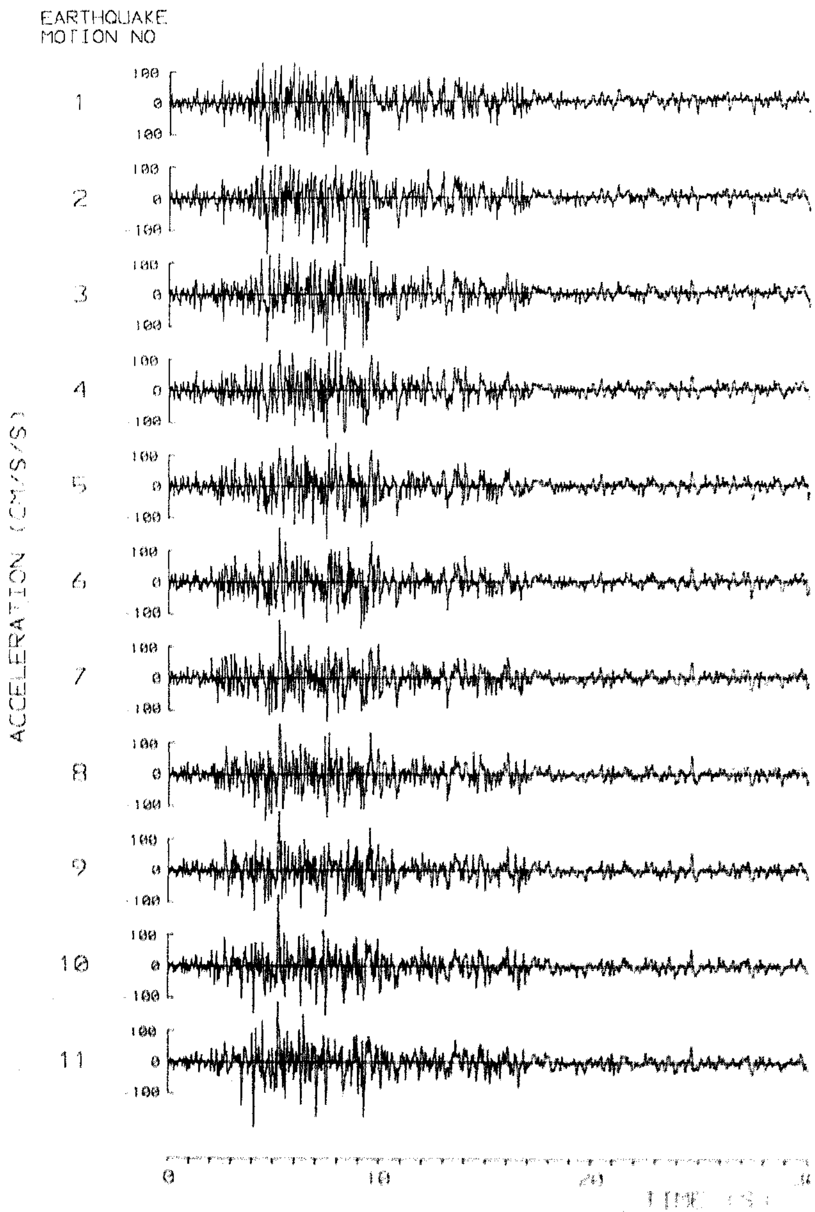

Fig. 2 - Time-histories of acceleration

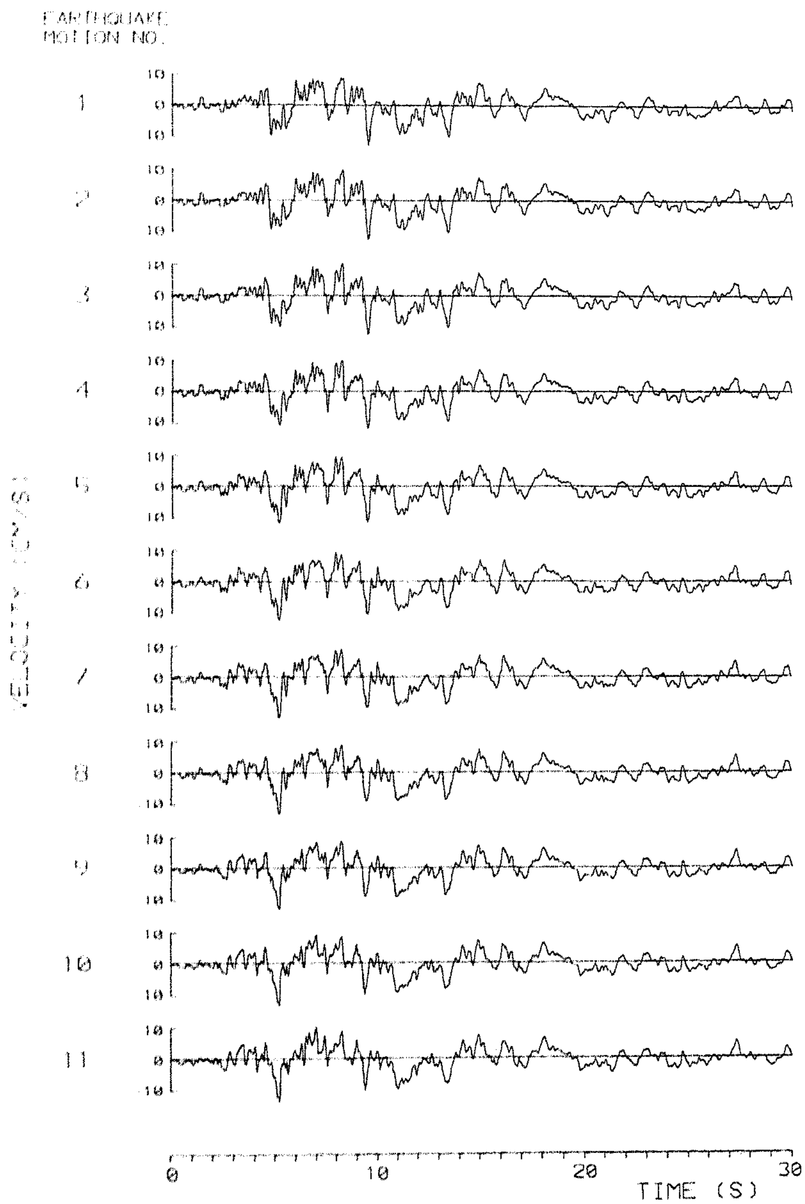

Fig. 3 - Time-histories of velocity

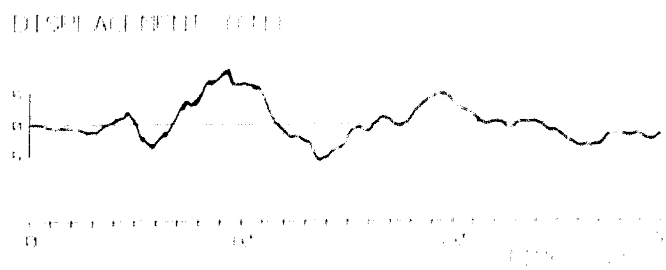

Fig. 4 - Time-histories of displacement (superposed)

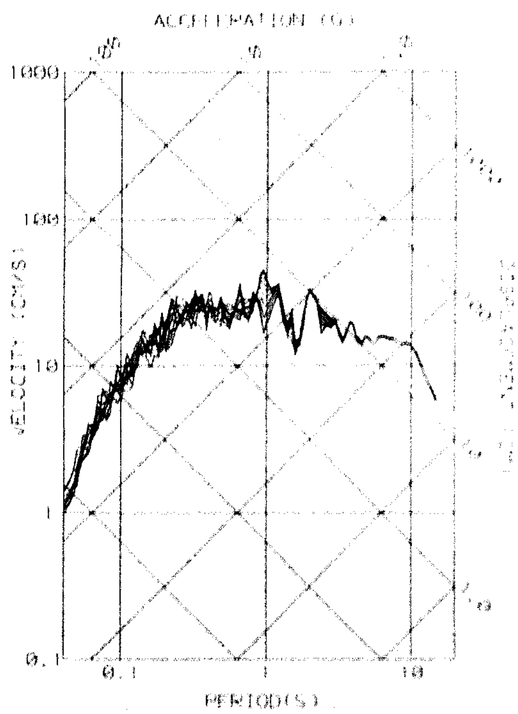

Fig. 5 - 2% damping response spectra for the motions at eleven points 100 m apart.

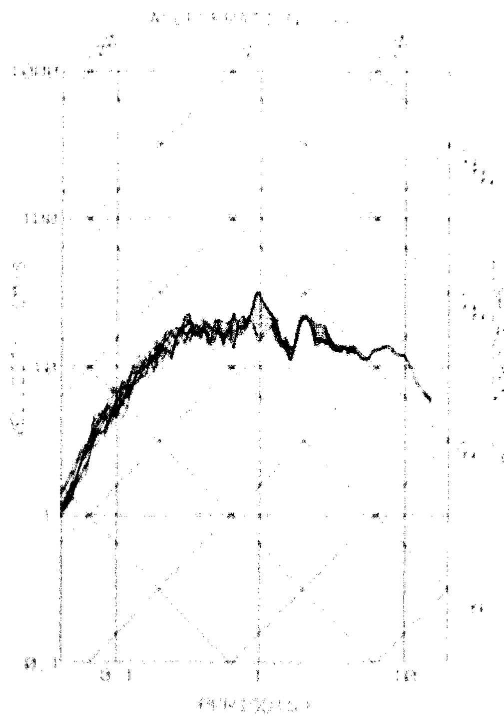

Fig. 6 - 5% damping response spectra for the motions at eleven points 100 m apart.