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Local spatial variation of earthquake ground motion

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ABSTRACT: In the study of spatial variation of earthquake ground motion from an engineering perspective, the focus is on the strong-motion portion of accelerograms at separation distances similar to those between foundation supports. The paper discusses problems in earthquake engineering requiring consideration of spatial variation and summarizes lessons learned from strong-motion accelerograph arrays, interpreted in light of random field theory.

1 LOCAL FIELDS OF GROUND MOTION

Local spatial variability of earthquake ground motion is important in damage assessment and microzonation. Almost identical structures at close distances may behave very differently during the same earthquake. Studies on spatial variation of ground motion aim to understand, describe and predict the local variability of ground motion parameters and local damage patterns. Such variation may be important in the design of structures with wide foundations such as dams, tall offshore structures, or nuclear plant facilities; structures with widely-spaced multiple supports such as bridges; and all kinds of "lifelines" carrying oil, gas, water, or traffic. A related critical question is how representative a single (recorded) time history is of the ground motion at points in its vicinity.The purpose of this paper is to provide an overview of research done to date on spatial variation, and to indicate its future potential and needs, with a focus on earthquake engineering.

1.1 *Different perspectives: engineers vs. seismologists*

Short-range spatial variation of earthquake ground motion is of interest to engineers and seismologists alike, but their perspectives differ. Seismologists seek to describe seismic wave composition, polarization, and source and path properties, while engineering interest lies in what is needed for response prediction, namely information about the energy-rich strong-motion phase which is often dominated by relatively high frequency components. Despite the many uncertainties of future earthquake ground motion at a site, its predictable aspects must be modeled with sufficient realism to achieve safe and economical seismic design.

1.2 *Interpretation of "local field"*

The term "local field", as used herein, refers to surface areas that are small enough that the internal variation of motion amplitudes with distance from the earthquake source, as expressed by attenuation laws, is negligible; specifically, within the confines of a "local field" (see Figure 1a), peak accelerations estimated in function of magnitude and distance differ negligibly compared to measurements of peak accelerations by (actual or hypothetical) closely-spaced accelerographs; these may differ by factors of 2 and more, even over distances of the order of meters. Each "local field" is understood to exist in a particular seismic setting characterized by faults or other seismogenic zones (see Figure 1b), and the seismic threat at the *extended site* can be defined by means of standard (site) seismic risk analysis.

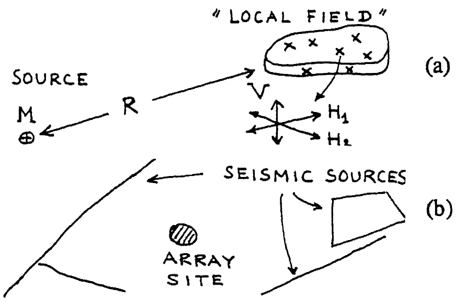

Figure 1. A *local field* of ground motion, perhaps the site of an dense accelerograph array: (a) with reference to a single earthquake; (b) in a seismological setting.

1.3 *Dense strong-motion accelerograph arrays*

Empirical data about spatial variation comes from dense arrays of strong motion accelerographs covering areas with typical dimensions ranging from several meters to several kilometers (see Figure 3). The first productive accelerograph array was the SMART-1 array located in Lotung, Taiwan (Bolt *et al* 1982). The array proper consists of 37 instruments synchronously measuring three ground acceleration components; it has recorded many earthquakes generating array-site ground motion levels severe enough to damage structures. Besides the main array, originally located in an alluvial valley — it has now been moved to a firm ground site — there were two recording stations on bedrock nearly. Inside the area covered by SMART-1, there is a much denser local array — the EPRI-Tai Power array (Abrahamson *et al* 1991) — centered on a 1/4th-scale model of a nuclear containment structure. Figure 3a sketches the still much denser layout of accelerographs at the Chiba Experiment Station operated by the University of Tokyo; this array and the EPRI-Tai Power array also have stations at depth, i.e., they are three-dimensional.

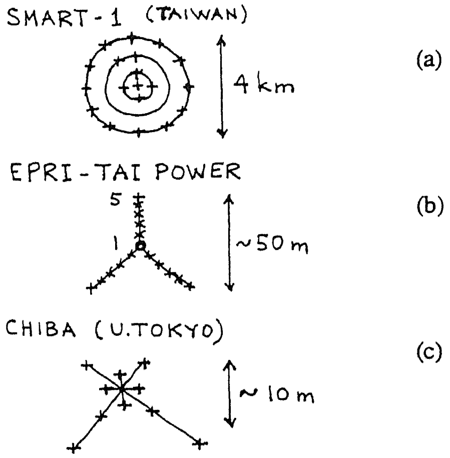

Figure 2. The lateral extent of dense strong-motion arrays covering different surface areas: (a) SMART-1 in Lotung, Taiwan; (b) the EPRI-Tai Power array, located inside the area of the SMART-1 array; and (c) the Chiba Experiment Station array (University of Tokyo).

1.4 *Applications in eartquake engineering*

Figure 3, self-explanatory, illustrates some of the topics in earthquake engineering requiring understanding of, and accounting for, local spatial variation of ground motion. Some of these have begun to be addressed, while others, remaining to be investigated, await the availability of more reliable empirical data from dense arrays (representing a broader range of local geological conditions, and earthquake magnitudes and source-to-array-site distances) and more robust analytical models of, for instance, spatial coherency functions.

2 STATE-OF-THE-ART ASSESSMENT

Indicative of the scope of research on spatial variation of earthquake ground motion and its recent progress is a special volume (Structural Safety, May 1991) entirely devoted to this topic, based on a workshop (held at Princeton University, sponsored by the U.S. National Center for Earthquake Engineering Research) which brought together an international group of earthquake engineers and seismologists for an in-depth exchange of information and views on spatial variability of ground motion, focused on earthquake engineering applications and needs. The papers provide a multi-perspective state-of-the-art assessment on spatial variation. Among the main themes covered: empirical findings from strong motion arrays; ground-motion models incorporating spatial variation; local-soil and kinematic effects due to spatially varying seismic input to foundations; seismic input for seismic analysis of lifeline systems; design criteria accounting for spatial variation; design of array configurations and array-data processing.

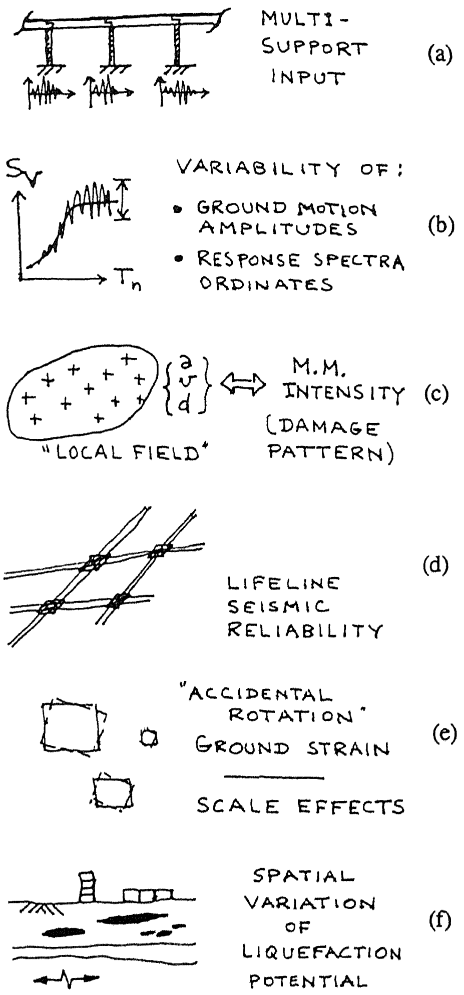

Figure 3. Indicating many practical uses in earthquake engineering of theory and empirical data (from arrays) about local spatial variation of ground motion.

Empirical results are presented based on SMART-1 by Bolt *et al.* (1991), Harichandran (1991) and Loh (1991) ; the EPRI-Tai Power array by Abrabamson *et al.* (1991) who sought to isolate systematic effects due to event magnitude by analyzing mainshock-aftershock pairs; and Chiba Experiment Station by Katayama (1991). Toksoz *et al* . (1991) present theoretical results for coherency of seismic waves in media with random heterogeneities. Menke *et al* (1991) compare results for explosion- and earthquake-induced motions. Somerville *et al.* (1991) focus on the effect of local site conditions e.g., different lateral heterogeneity, on incoherency. Celebi (1991) presents case studies of topographical and geological amplification and assessing what they imply for codes and microzonation. Zerva & Shinozuka (1991) present a theoretical model to predict differential ground motion statistics in terms of source parameters (rupture velocity, dislocation amplitude, and rise time).

Kinematic interaction for partially coherent free field motions is an effect of interest to foundation engineers. Rigid foundations tend to average out high-frequency components but may undergo 'accidental' rotation (torsion and rocking); these concepts are applied to the seismic response of broad-base North Sea platforms by Nadim *et al.* (1991). Oliveira at al. present a ground motion model for multiple-input structural analysis. Tassoulos & Roesset (1991) review studies on wave propagation in sediment-filled valleys and propose a two-dimensional rectangular-valley model applied to the Valley of Mexico. Needs in lifeline system analysis are highlighted by Eguchi (1991). The results described in the sections 3, 4 and 5 are based mainly on research by the writer and his collaborators at Princeton University and at MIT (Fenton 1991; Boissieres 1992; Vanmarcke, Heredia & Fenton 1991; Fenton & Vanmarcke 1991a,b; Cunniff & Vanmarcke 1988; Boissieres & Vanmarcke (1991); and Harichandran & Vanmarcke 1986)

3 LOCAL-FIELD GROUND MOTION MEASURES

3.1 *Variability of ground motion parameters*

Array recordings of a seismic event may be thought of as incomplete observations of a space-time random field, with partially predictable phase lags; the "aligned" motions — from the time lags owing to wave-front propagation have been subtracted — are assumed to be "locally" homogeneous and isotropic during the strong motion phase. On this basis, one can construct histograms and compute measures of dispersion for ground motion parameters such peak amplitudes, Arias intensity, and strong-motion durations; the width of the histograms depends on magnitude and distance and local geological conditions, as well as on the surface area covered by the accelerographs and (to some extent) on the configuration of the array; see Figures 4 and 5.

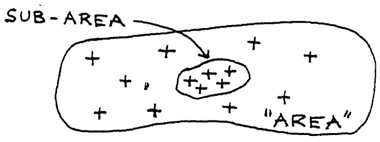

Figure 4. Variability of ground motion parameters (like peak amplitudes) depends on the area covered by the accelerographs providing data; one expects dispersion to grow as the local-field's area increases.

3.2 *Measures accounting for differential motion*

Besides the classical measures of the ground motion "at a point" (whose variability from point to point, for a given earthquake, can be quantified at an array site), there are a number of quantities of engineering interest that relate explicitly to the motions at two or more closely-spaced points or to the aggregate motion within "blocks" of (near-surface) material; see Figure 6.

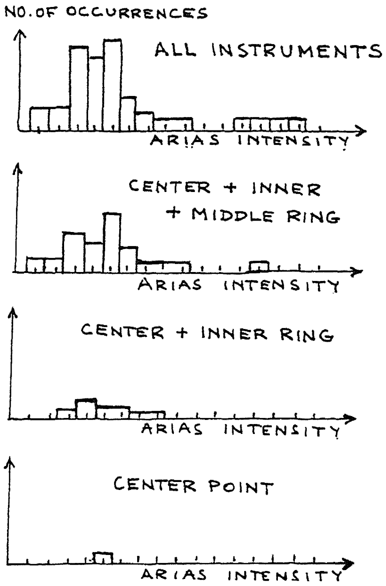

Figure 5. Histograms of "Arias Intensity" (integral of squared accelerations) for different circular areas at the SMART-1 array site; for Event 5, NS-EW direction; indicates growing dispersion as the area increases.

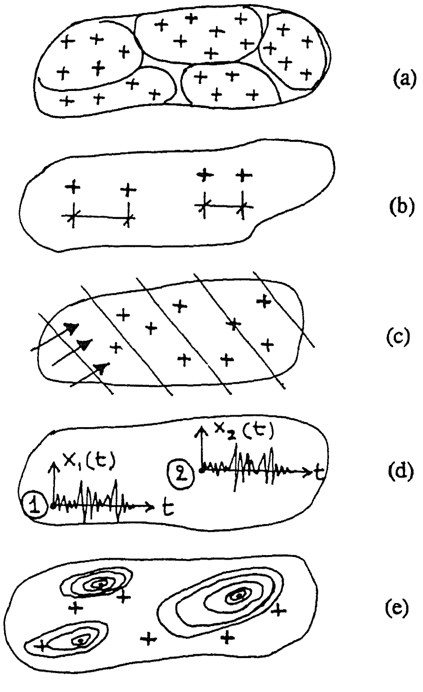

Figure 6. Measures which account explicitly for spatial variation: (a) local averages and local deviations from local averages; (b) differential motion and strain fields; (c) patterns of time lags, indicating apparent velocity of propagation and local deviations; (d) spatial correlation between pairs of "time histories"; and (e) local spatial extremes or "hot spots" of, say, peak acceleration.

4 TIME LAGS AND CORRELATION DECAY

4.1 *Methods of array-data processing*

The spectral density function, along with the strong-motion duration, provide a logical and tractable format for predicting structural response as well as for relating ground motion frequency content to earthquake source parameters, epicentral distance, and site conditions, and, in a random field context, for incorporating data on local spatial variation by means of frequency-dependent spatial correlation functions (Vanmarcke 1976, 1983). As a starting point, the spectral density function of, say, the horizontal component of ground motion, averaged over all (triggered) array stations is partitioned, as in the example in Figure 7, into components centered at 1, 3, 5 and 7 Hz. for the express purpose of quantifying frequency-dependent spatial correlation.

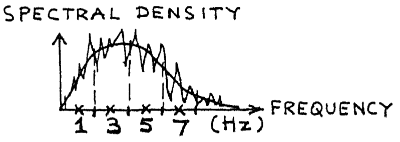

Figure 7. Spectral density function of, say, horizontal ground motions, spatially averaged across an array; it is divided into non-overlapping narrow frequency bands for frequency-dependent spatial correlation analysis.

When analyzing a pair of ground-motion time histories, or rather, the synchronized strong-motion parts thereof, at two array locations — see Figure 8 — one option is to work with the non-decomposed accelerograms or the corresponding (computed) displacement time histories. The second option is, as indicated above, to decompose each motion into narrow-band contributions centered on a prescribed set of frequencies.

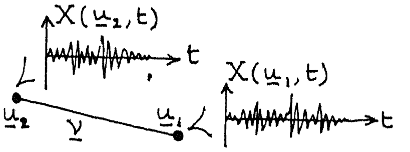

Figure 8. Ground-motion time histories at two points, showing spatial and temporal coordinates.

4.2 *Composite "time lags" in the strong-motion phase*

The "lag" is a time shift applied to the "strong-motion wave train" of a particular component of the grond motion in the direction of seismic wave propagation (the epicentral direction) such that it maximizes the cross-correlation between a pair of recorded accelerograms. One generally obtains a clear determination of the lag when two array stations are close, and it gives as well an estimate of the coefficient of cross-correlation at the particular separation distance, as illustrated in Figure 9.

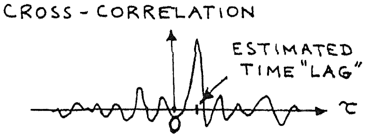

Figure 9. Cross-correlation as a function of time shift τ in the epicentral direction; the value of τ maximizing the cross-correlation is the estimated "lag", providing one point in Figure 10. The *peak* cross-correlation can be plotted versus separation distance; see Figure 13.

Repeating this estimation for many pairs of points at an array site (for a given earthquake), relying on the need for "closure" (involving any triplets of locations), yields a full set of interrelated "lags" with respect to a single reference point such as the center instrument (C00) at the SMART-1 site (Boissieres 1992). As shown in Figure 10, this allows one to plot the lags as a function of the separation distance projected in the epicentral direction; to estimate an apparent propagation velocity across the array site; and to evaluate the statistics of the "residuals" which reflect "details" of the site geology and/or the complexity and spatial extent of the source, as well as the dependence on frequency of the wave velocities. Despite the fact that the SMART-1 array is sited on a soft-soil overburden, typical apparent wave propagation velocities (like 3740 m/s in Figure 10) reflect the properties of the underlying bedrock; the residuals may be due mainly to the different distances (depths of overburden) and wave velocities of *upward propagation* through the soft near-surface layers.

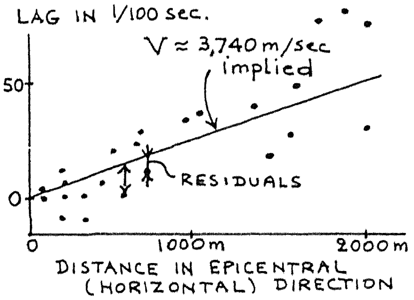

Figure 10. Linear regression of lag (in units of 1/100 s) vs. separation distance — SMART-1 array, Event 5, EP motions. Implied propagation velocity is 3740m/s; the standard deviation of the residuals is 15.5 "units" and the "r-square" value is 0.758.

4.3 *Non-parametric estimation of spatial correlations*

Boissieres (1991) develops and applies new statistical methods to obtain non-parametric estimates of spatial correlation between any station and all other stations at an array site, allowing the correlation structure to be non-isotropic and heterogeneous. We show typical results for strong-ground-motion acceleration (in Figure 11) and displacement (in Figure 12) for a horizontal component of motion recorded during Event 5 (local magnitude 6.3; epicentral distance of the array center point, 30 km) at the SMART-1 site. Similar results are obtainable for frequency-centered, band-limited motion components, but are of limited value to engineers interested in *predicting* future ground motion at sites other than those where arrays happen to be located.

4.4 *Spatial correlation functions*

The *composite* spatial correlation as a function of separation distance is shown, for acceleration during the same SMART-1 event discussed above, in Figure 13.

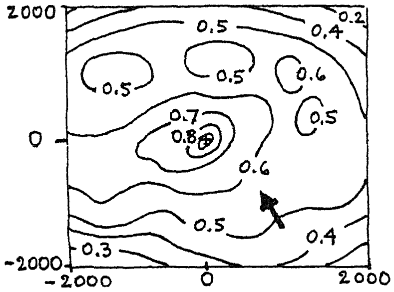

Figure 11. Results of non-parametric estimation of (composite) spatial correlation with center station COO (SMART-1, Event 5, EP component) for strong-motion ground acceleration.

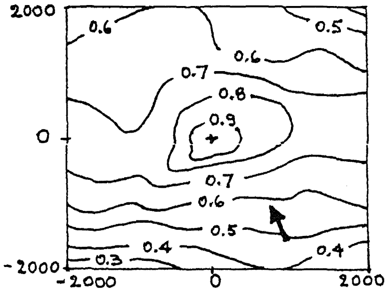

Figure 12. Results of non-parametric estimation of (composite) spatial correlation with center station COO (SMART-1, Event 5, EP component) for strong-motion ground displacement.

Also shown are the results (again for the same event and motion component) of the *frequency-dependent* correlation for frequency bands centered at 1, 3, 5 and 7 Hz, resp. (Harichandran & Vanmarcke 1986). Theory of homogeneous space-time random fields (Vanmarcke 1983) indicates how the *composite* and (frequency-dependent)*component* correlation functions are related: the composite correlation at a given separation distance equals a weighted average of the frequency-dependent correlation, and the weights are the unit-area spectral density function. To obtain the composite *displacement* correlation, it suffices to use the unit-area displacement spectral density function, which is proportinal to the acceleration spectral density function and inversely proportional to the fourth power of frequency. The procedure is bound to give rise to higher composite correlation for displacements than for accelerations, as is also evident when one compares Figures 11 and 12.

An interesting aspect of the correlation functions is their peculiar pattern of decay with separation distance; its "apparent" scale of fluctuation depends on the array configuration (i.e., distances between stations, typical overall dimension); no simple or so-called "single-scale" correlation function (Vanmarcke 1983), such as the exponential function, captures the complexity of the implied "fractal" correlation decay pattern.

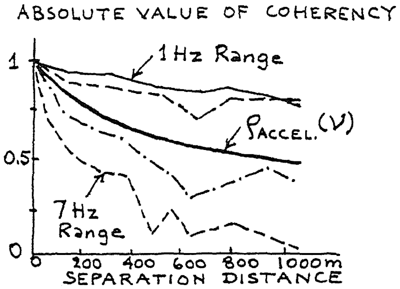

Figure 13. Typical set of results for correlation decay with distance, for horizontal motion (SMART-1, Event 5, EP component). Figure shows both the "composite correlation" — the solid curve in the middle — and a set of frequency-dependent correlation functions, indicating more rapid decay the higher the frequency.

High-frequency ground motion components tend to be weakly correlated in space; one practical consequence is that their effect on structures, owing to forced spatial averaging across rigid foundations, is less than is implied by individual accelerograms (see Figure 14); "accidental" rotation is another space-related kinematic effect. Using random field theory, we developed tools for quantifying the effect of local spatial averaging on 'point' spectral density functions and response spectra; and cross- spectral density matrices to be used as input into stochastic seismic analysis of multi-support or spatially extended structures (Vanmarcke 1989).

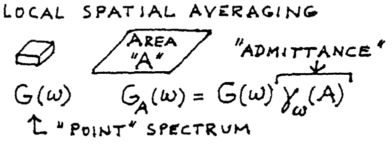

Figure 14. Effect of local spatial averaging on the spectral density function; high-frequency components are averaged out, reducing the peak input acceleration.

5 SIMULATION OF GROUND MOTION FIELDS

The Special Volume on spatial variation of ground motion reports simulations of local fields of ground motion by Shinozuka & Deodatis (1991) and, based on ARMA (auto-regressive, moving-average) methods, by Ellis & Cakmak (1991). Vanmarcke & Fenton (1991) present a technique of 'conditional simulation' of free-field ground motions with known space-time correlation structure which can also be made to match recorded

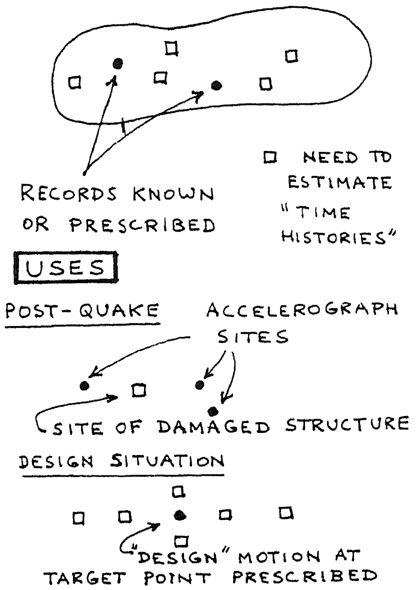

Figure 15. Conditioned simulation of earthquke ground motion, in which artificial motions possess prescibed space-time correlation structure and are consistent with known or prescribed motions at certain points. Practical uses of this capability are indicated.

accelerograms at prescribed surface locations; see Figure 15. This method can be used to "predict" ground motion at a location (such as the site of a damaged structure) close to one or more accelerograph stations, or to generate input for seismic analysis of spatially-extended structures when the "design" motion at target point has been specified. Slow evolution of the ground motion frequency content can be accounted for in these simulations through so-called evolutionary spectra.

6 CONCLUSIONS

New data from dense arrays and improved analytical modeling techniques enable earthquake engineers to consider local spatial variation, along with temporal variation, of seismic ground motion input to structures. All structures are to some degree "spatially extended", and spatial variation is obviously important for multi-support input, ground strain prediction, liquefaction, microzonation, and lifeline reliability. Local fields of ground motion connote variability over short distances of ground motion parameters, and spatial correlation makes updating, *conditioned* simulation, and informed data acquisition planning feasible and meaningful. More dense-array data and related data analysis is needed to achieve robust models of spectral density and spatial coherency functions for different magnitudes, epicentral distances, and local geological conditions.

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