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The state of the art in synthesis of strong ground motion for earthquake engineering

Bruce A. Bolt
Department of Geology and Geophysics and Department of Civil Engineering, University of California, Berkeley, Calif., USA

ABSTRACT: The engineering demand for realistic seismic wave inputs for design and response studies has shifted emphasis in recent years. The effectiveness of building codes and ground intensity zoning maps has been tested in a number of recent large earthquakes, such as Loma Prieta, 1989, Erzincan, 1992, and Landers, California, 1992. The observational basis for seismic strong motion variability is much firmer after the addition of many new accelerograms from California, Japan, Europe, and elsewhere. As a result, engineering requirements have expanded from simple spectrum scaling, using (high frequency) peak-ground accelerations, to emphasis on full seismograms, frequency-dependent intensity mapping, spectral attenuation and appropriate seismological wave phasing. For critical structures, checks for nonlinear responses now involve analysis in both the time and frequency domain. Multi-supported and base-isolated structures and soil-structure interaction adjustments require the incorporation of ground displacement histories and coherency functions in the synthetic inputs. The main methods of ground motion synthesis at present are fourfold: record selection and scaling, statistical spectral generation, elastic dislocation theoretics, and matched estimated parameterization. These methods will be briefly reviewed with emphasis on the nonlinear algorithms involved in the last procedure. The strengths and weaknesses of finite element path and source modelling and the Green's function empirical construction will be discussed. Recent illustrations of iterations to match target parameters will be given from the predicted ground motions for long bridges and viaducts in the San Francisco Bay Area.

1 INTRODUCTION

Although analysis of strong earthquake motion is a relatively vigorous part of present day seismological research, there are many aspects which remain undeveloped. The reason is the continued lack of actual closely-spaced measurements of large amplitude seismic motions near to large seismic sources. There are, for example, as yet few records of ground accelerations recorded by strong motion instruments in the near field of earthquakes above magnitude 7.5. An important set of accelerograms (see Figure 1) was obtained in Central California in the 1989 Loma Prieta earthquake (MS = 7.1, ML = 6.7). These have provided a starting point for studies of the seismic response of San Francisco Bay bridges now being undertaken.

On the theoretical side, it has been demonstrated that reasonably accurate synthetic seismograms can be computed using appropriate Green's functions (Irikura, 1983; Hartzell, 1985; Hutchings, 1991; Somerville et al., 1991) or records of small earthquakes as impulse responses. Recently, a valuable introduction to this problem has been given by Mikumo & Miyatake (1987). These authors point out that for predicting strong motions from a large earthquake, the complex dynamic rupture processes of the fault, the heterogeneous crustal structures along the source propagation path and near the recording site must be allowed for.

Because of the difficulty, in situations where these details are unknown, of incorporating a full theoretical description into the synthesis process, another approach is to combine theory and the limited observational measurements. This paper is concerned mainly with this semi-empirical method (Spudich & Archuleta, 1987).

The contribution of strong motion seismology is to explain high amplitude seismic waves near a seismic source and to use such measured motions to infer pro-

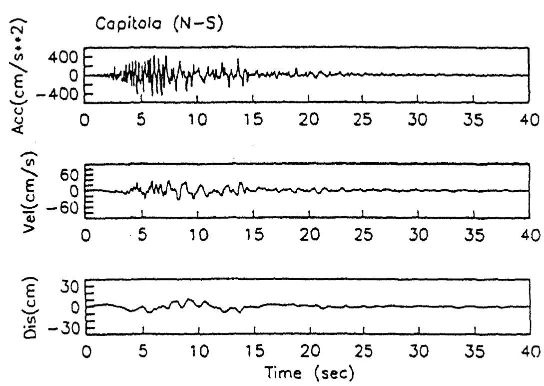

Figure 1. Ground motions recorded at Capitola, California, in the 1989 Loma Prieta earthquake.

perties of the source, propagation path and predict ground motions at the recording site (Hartzell & Heaton, 1983; Boatwright, 1988; Hartzell & Mendoza, 1991). An important part of such research is directly applicable to seismic risk assessment and earthquake engineering. The final synthesis must be carefully defined if it is to be used in the construction of realistic seismic inputs to analyze critical structures. For example, advanced engineering studies now incorporate the *phase* of seismic wave motions that shake structures.

Specifically, structures with multiple supports respond so as to average the free-field accelerations incident upon the supports. Hence, dynamic analysis of these structures requires suitably phased time histories applied at each support or a modal response analysis with complete phase information appropriate to the local tectonic zone. In the past, the usual engineering response spectrum described only the amplitude of the oscillatory motion and did not define the phase behavior. In reality, for viaducts, large bridges, and dams, out-of-phase wave motions over inter-support distances cause differential ground accelerations and differential rotations along the base of the structure. Thus, complex spectral representation must be used.

The most obvious case arises for non-vertically propagating seismic waves which produce systematic phase shifts between support points with significant incoherency. These travel-time lags are reinforced by the mixing of out-of-phase motions produced in other ways such as wave scattering.

Recently the measurement of such effects has become feasible from dense strong motions arrays with absolute times. The array recordings have provided opportunities to study phase changes and coherency in seismic ground motions over various distances and to estimate their effects on large engineering structures (Bolt et al., 1982). Phasing may be incorporated through the definition of a response phase spectrum which is consistent with the response (amplitude) spectrum. This method allows the routine calculation of the response phase spectrum for ground acceleration, ground velocity, and ground displacement (Abrahamson & Bolt, 1985).

At the present time, the use of coherency in engineering practice has been limited and is probably necessary only in critical cases. Nevertheless, the importance of the relevant engineered structures suggests that the methodology will expand into practice because of the reduction in vulnerability and overall construction costs. The incorporation of phase shifts generally, but not always, leads to a reduction in structural response relative to in-phase input motions and hence reduces nonlinear structural effects.

2 SEISMIC WAVE PATTERNS

Strong ground motion consists of a mix of seismic waves as described by elastic wave mechanics. Seismic shaking at a site arises from the superposition of different elastic wave types, with time as an independent variable. An earthquake is rarely stationary in time but varies in amplitude A, frequency ω (radians per sec), and wavelength λ, from time window to time window. This motion can often be represented by the sum of simple
harmonic (advancing) plane waves. Each wave can be signified by a wave number, k, where $k = 2\pi/\lambda$.

The standard assumption in multiple support or array analysis is that the record consists of a deterministic signal plus noise. For example,

$$u_j(t) = u(\mathbf{x}_j,t) = s(t) + \varepsilon(\mathbf{x}_j,t), \qquad (1)$$

where $u_j(t)$ is the output (acceleration, velocity, or displacement) of the jth accelerometer at position $\mathbf{x}_j$, $s(t)$ is the deterministic signal, and $\varepsilon(\mathbf{x}_j,t)$ is the noise. The form of equation (1) assumes that the signal arrives simultaneously at each station. This condition is satisfied by introducing a delay τ_j to the output of the jth accelerometer. For a plane wave, the delay is

$$\tau_j = \mathbf{k}.\mathbf{x}_j \;/\; \omega, \qquad (2)$$

where $\mathbf{k}$ is the vector wave number and ω is the frequency of the plane wave.

In some analyses it is sufficient to consider a single harmonic component of the strong motion record

$$s(\mathbf{x},t) = \mathrm{A}\cos(\mathbf{k}.\mathbf{x} - \omega\, t + \delta), \qquad (3)$$

where A and δ are constants. The wave velocity is $c = \omega/|\,\mathbf{k}\,|$.

In equation (3) the angle δ is called the phase angle because $s = \mathrm{A}\cos\delta$ represents ($\mathbf{x} = 0$, $t = 0$) an advance (or delay) of the constituent wave harmonic. In computing phased synthetics, the phase angles δ are key parameters.

Alternatively, the time domain representation given by equation (3) is transformed to an equivalent frequency description. The wave field is then expressed as a three-dimensional Fourier transform. Because a Fourier transform is a complex variable, the complete representation of a time history requires an amplitude spectrum plus a phase spectrum. The different phase spectra of often-used accelerograms are sometimes used to generate an artificial but more suitable time history by interchange of phase spectra. This substitution procedure preserves the amplitude spectra and maximum motions but varies the duration and phasing pattern. As mentioned earlier, in engineering applications to structures with a rigid base or single input point, the response phase spectrum is usually unimportant and is ignored.

The construction of synthetic time histories requires the correct inclusion of different types of seismic waves with their theoretical interrelationship (see Bullen & Bolt, 1985, for a full description). In most applications, three types of seismic waves need consideration: compressional (P) waves, shear (S) waves, and surface (Love and Raleigh) waves. As P, S, or surface waves propagate through the rock or soil strata, one type of wave may generate waves of another type, and phase shifts δ occur as waves are reflected or refracted.

The seismic zone is highly significant because the location, size, and type of seismic source and the propagation path may affect the total motion strongly. If the waves all emerged from a point source, then phasing, or order of arrival, at a series of support points would depend only upon the particular wave velocity. In fact, earthquake waves are radiated from many points along an extended fault slip and depend on the type of slip involved. In the 1989 Loma Prieta earthquake in California, this slipped area was about 40 km long and 20 km deep (Steidl et al., 1991; Wald et al., 1991). Waves from different parts of the ruptured fault are thus delayed by various amounts due to the different distances that they travel from their source points to the station. Inhomogeneity of geological structures near the site also causes significant wave scattering.

It follows that between seismogenic zones a set of strong motion seismograms, constructed as boundary conditions at the various structural input points, will not in general be alike. A measure of the *likeness* of two wave trains is given the technical name *coherency*, and quantitative measures can be obtained in the time domain (through simple cross-correlation) or in the frequency domain. In the frequency domain, the (complex) coherency between sites 1 and 2 is

$$\delta_{12}(\omega) = S_{12}(\omega) / [S_{11}(\omega)\, S_{22}(\omega)]^{1/2}\,, \qquad (4)$$

where S_{ij} is the cross-spectral matrix.

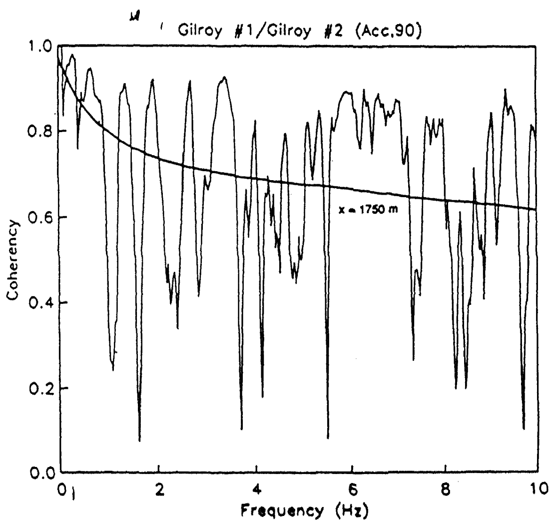

Figure 2. The coherency function (equation (4)) computed from adjacent (1750 m separation) recordings of strong motion in the Gilroy strong motion array during the 1989 Loma Prieta main shock. The heavy line is a smooth representation of the coherency effect.

Studies of the coherency of strong ground motions have now been published (see Abrahamson & Bolt, 1987), and a few have been incorporated into structural response analyses for critical structures as part of soil-structure interaction calculations. When numerically modelling with realistic synthetic sets, a test of coherency attributes is recommended.

3 NUMERICAL SYNTHESIS OF STRONG MOTIONS

Numerous methods and examples of synthesizing seismograms in the near field of a large seismic source have been published (see, for example, the book *Seismic Strong Motion Synthetics*, 1987). A numerical construction process for prediction of semi-empirical but realistic strong ground motions is now outlined. The computation of such site dependent and phased time histories is not unique, and a number of alternative methods are available (see, e.g., Joyner & Boore, 1988; Vidale & Helmberger, 1987; Cohee et al., 1991).

The first step is to define, from geological and seismological information, the appropriate earthquake sources for the site of interest. The source selection may be deterministic or probabilistic and may be decided on grounds of acceptable risk (Bolt, 1991). Next, specification of the propagation path distance is needed, as well as the P, S, and surface wave velocities in the zone. These speeds allow calculation of the appropriate wave propagation attenuation (Abrahamson & Litehiser, 1989) and delays between support points and the angles of approach of the incident waves.

The construction of realistic motions proceeds as a series of iterations from the most appropriate observed strong motion record already available to a set of more specific time histories which incorporate the seismologically defined wave patterns. Where feasible, strong motion accelerograms are chosen which satisfy the seismic source (dip-slip, etc.) and path specifications for the seismic zone in question.

The iterative process is controlled by applying seismological (Kanamori & Anderson, 1975) and engineering constraints. For example, the response amplitude spectra should fall within one standard error of a specified target spectrum obtained, say, from previous data analysis or an earthquake building code (Lilhanand & Tseng, 1988). Similarly, each seismogram must maintain prespecified peak-ground accelerations, velocities, and displacements within statistical bounds. The durations of each wave section (mainly P, S, and surface wave portions) of each time history must also satisfy prescribed source, path, and site conditions. At the present, automatic convergent algorithms are not available for reliable constructions, so that experience with observed seismograms and knowledge of seismic wave theory are needed.

3.1 *Illustration from San Francisco Bay*

After the damage to the San Francisco Bay Bridge and the I-880 elevated roadway in the 1989 Loma Prieta earthquake, new considerations were given to the appropriate design criteria for large structures in high seismic hazard zones. The California Department of

Transportation, for example, initiated thorough ground motion studies for its existing and future bridges and viaducts in the San Francisco Bay Area and elsewhere.

The large size of such structures focused attention on relatively long period seismic motions, i.e., from 2 Hz to 5 sec or more. It should be remembered that for energetic S wave components (see equation (3)) of period about 1 sec, the wave lengths λ incident on the supports are of the same order as key structural dimensions. Hence, specifications for these studies required consideration of coherency factors. The studies have challenged the state of modelling knowledge. First, no strong motion records were available for large near-earthquakes in the Bay Area that measure the spatial variation of shaking over distances of many hundreds of meters (e.g., long spans for the Bay Bridge and the Golden Gate Bridge). Secondly, compatible ground velocity and displacement time histories, essential input for structural analysis, were also unavailable.

As an example, let us consider construction of a synthetic set of phased ground motions (horizontal component) suitable for structural seismic response analysis of the eastern section of the San Francisco Bay Bridge. The bridge is about 3 km long with its eastern end situated about 5 km from the active strike-slip Hayward fault. This fault ruptured last in 1868, producing a magnitude 7.2 earthquake. The required design motions are chosen to represent a repetition of this even.

Let us now choose two neighbouring input points for the Bay Bridge, called E23 and E17, a distance of 613 meters apart, with peak-ground accelerations of 0.55g and 0.53g, respectively, after allowance for distance attenuation. The bridge supports are actually almost all located on recent sediments of varying depth, but in the following, rock sites will be assumed. (Allowance for the soils can be made at a later stage by soil engineering methods.)

The initial accelerogram chosen for site E23 is horizontal ground motion recorded at Capitola on firm ground, 10 km from the fault source of the 1989 Loma Prieta earthquake. The ground accelerations, velocities, and displacements are shown in Figure 1. These records are then scaled to the required peak acceleration for E23 and the 5 percent damped response spectrum calculated (Figure 3). In Figure 3, a design spectrum developed for the extensions to the Bay Area Rapid Transit System (BART) is compared with that of this initially assumed ground motion. A ratio function between these two response spectra is then used to iterate the Fourier spectrum so that compatibility with this smoothed target spectrum is achieved (Figure 4). This non-linear process produces a realistic motion for site E23 (Figure 5). This synthetic motion has a wave pattern, duration, amplitude, and spectrum that meet the seismological and engineering criteria for a source, site, and structure of the kind involved.

Next, incoherency must be introduced for the adjacent input point, E17. The first step is simply to lag the phase at each wavelenth of the E23 record to allow for the wave propagation. Because no coherency function

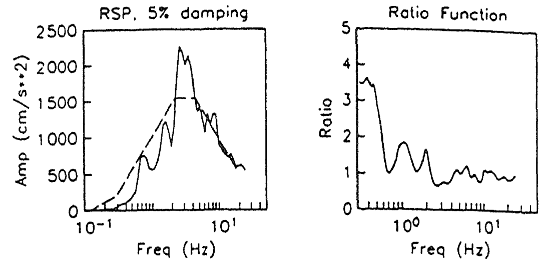

Figure 3. Response spectrum for the Capitola motion (Figure 1) compared with a target code spectrum. On the right, the ratio of frequency components is shown.

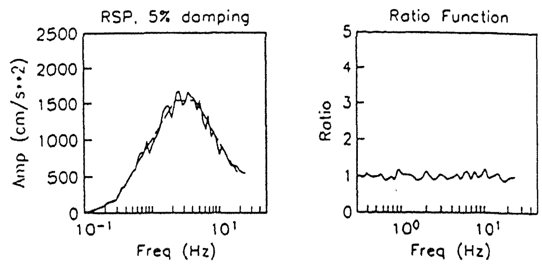

Figure 4. Four iterations of the Fourier amplitude spectrum (phase fixed) of the Capitola record produced the compatibility shown.

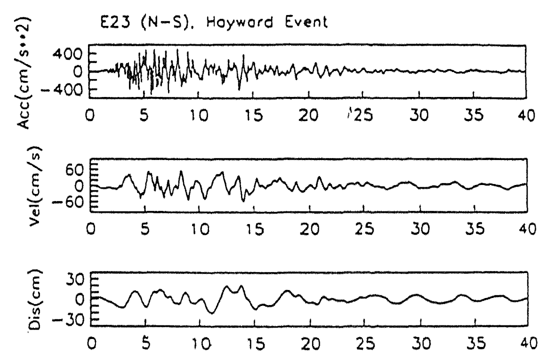

Figure 5. The synthesized ground motions for site E23 (on rock) for a magnitude 7.2 earthquake, generated by shallow fault rupture about 5 km away.

(equation (4)) has been measured for the geological region around the Bay Bridge (see Bolt et al., 1982), an acceptable substitute function is required. This function was computed from two horizontal-component ground accelerations at neighbouring sites near Gilroy (Figure 2), also from the 1989 Loma Prieta earthquake. (The interstation distance of 1750 m was the shortest available.) The smooth line in Figure 2 represents a target which the coherency function between motions at E23 and E17 should achieve.

The process was to adjust the Fourier phase spectrum for the E23 record in Figure 5 pointwise by a suitable shape function until the target coherency function was matched within reasonable bounds. The modified Fourier complex spectrum was then formed back to the time domain and the time history rescaled to the specified peak-ground acceleration (0.53g). The resulting phased accelerogram is reproduced in Figure 6.

In this example, because the intersite distance (613 m) is not large relative to the wave lengths of most engineering interest (corresponding to 5 to 0.5 Hz), the differences between the E23 and E17 motions are not great. Over many bridge spans, however, the dynamical effects become significant.

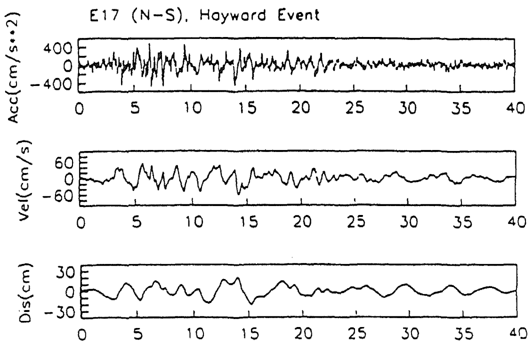

Figure 6. The phased synthetic ground motion for site E17 (on rock) which is compatible with the motion (given in Figure 4) at E23.

4 CONCLUDING REMARKS

The verification of artificial ground motions is impossible in many cases because no relevant recorded seismograms are available. Acceptability for engineering design purposes is enhanced by minimizing the range of extrapolation from records of moderate magnitude earthquakes such as Loma Prieta, 1989, and Erzincan, 1992, to the larger design earthquake. Records from the recent Landers, California, earthquake ($M_S = 7.5$) will fill a gap. The case of synthesizing realistic ground motions for earthquakes from blind thrust faulting remains a special challenge.

The discussion here does not take up the difficult question of effects of non-linear soil response at the site (Darragh & Shakal, 1991). When two-dimensional soil structure response is involved, the problem is to provide the different types of seismic waves separately in the rock synthetics.

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