CHARACTERIZATION OF EARTHQUAKE GROUND MOTION

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SUMMARY

Concepts developed in seismology as well as information obtained from empirical study of earthquakes are highlighted. Their use in characterizing earthquake ground motion and a method for simulating time histories of acceleration is proposed.

INTRODUCTION

The design profession currently has access to individual earthquake records and/or design spectra for the design and/or safety assessment of facilities located close to faults. This paper addresses the issue of improved representation of the strong ground motion for these purposes. A hybrid approach based on concepts developed in seismology as well as information obtained from investigations of observed earthquake records are described. The use of such a procedure for characterizing the ground motion is explored, its physical significance is examined and lastly its usefulness in generating time histories of ground motion is investigated.

SEISMOLOGICAL CONCEPTS

An earthquake is the result of a displacement discontinuity sweeping a fault plane. This idea of the earthquake mechanism is the one generally accepted by seismologists, at least for shallow earthquakes which are of interest to us. The different series of events which constitute the seismic cycle are (i) accumulation of potential energy on the two sides of the fault, (ii) a critical phase in which a catastrophic instability occurs, (iii) rupture propagation on the fault plane and its eventual stopping, and (iv) a transition to a new equilibrium on the fault plane (Ref. 1).

The stored potential energy which is released during rupture in the form of kinetic energy is radiated outwards from the fault plane. Early work in modeling the earthquake source made use of kinematic descriptions of the displacement discontinuity propagating on a prescribed surface of the fault plane. The displacement discontinuity on the fault is mathematically equivalent to a planar distribution of double couples. The wave radiation at a receiver station is then calculated assuming the source is embedded in a homogeneous, isotropic, linear, elastic, unbounded medium (Ref. 2). Later on, more sophisticated models of the intervening medium between the source and the receiver station have been incorporated. The main advantage of these source models are their simplicity and though many of them are physically unrealizable, they are still used to describe gross features of displacement records.

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A different approach based on fracture mechanics of a crack initiated in a pre-existing tectonic stress field on a prescribed fault plane has recently been the subject of extensive study by seismologists. In this approach, called the dynamic model, the amount of slip, the rupture propagation, etc., are obtained by solving a mixed boundary value problem. Analytical solutions of the dynamic model which have been obtained so far are valid for crack growth and are incapable of including the stopping of the crack. Effects of crack stopping can only be obtained by numerical schemes (Ref. 3). The dynamic models provide us with more realistic slip distributions and these in turn have been used as guides in the selection of physically more realizable kinematic descriptions of slip on the fault plane.

Studies of generation of seismic waves using a kinematic or dynamic model of the earthquake source embedded in a realistic earth model has been conducted by seismologists. In the initial stages their interest was primarily focused on displacement records. Some attempts to use these models to describe acceleration records were made but it became increasingly clear that the early source models which treated the rupture as propagating coherently were quite inadequate to model acceleration. The ground acceleration during an earthquake has a rather complicated waveshape, and is richer in higher frequencies than either ground displacement or ground velocity. The relation of the Fourier spectra of the acceleration to the Fourier spectra of velocity and to the Fourier spectra of displacement is given by Eq. 1:

$$|A(\omega)| = w|V(\omega)| = \omega^2|D(\omega)| \tag{1}$$

The civil engineering community whose experience was with acceleration records had already recognized the complex waveshapes of the high-frequency components *in the acceleration record and suggestions were made to model these as random processes* (Ref. 4).

As the acceleration record is made up of relatively higher frequencies, which correspond to lower wavelengths, details of the faulting process as well as changes in the structure of the intervening medium are needed at reduced length scales. In most cases we just do not have this sort of detailed information and even if we had it, the computational task would be prohibitively expensive. The effect of the details of the faulting process is a complicated pattern of wave arrivals which is evident in acceleration records at all distances from the fault. In addition, the changes in the structure of the intervening medium result in additional complexities, the effect of which is to reduce the coherency between two records even if they are from stations which are close to each other.

The first attempts to model the "random," high-frequency components in the acceleration records were concentrated on randomization of the rupture propagation. The rupture propagation was randomized (Ref. 5) and the accelerations computed for even a linear, elastic, unbounded medium showed increased high-frequency components. Since then other researchers have used different randomized models of the rupture propagation and the notion that the generation of high-frequency components are intimately connected to the details of the energy release at the fault plane has been accepted by seismologists. The later models in which the rupture proceeded randomly were described as incoherent source models in contrast to the early models in which rupture propagated smoothly.

Concurrent with work done on theoretical modeling of the earthquake source and wave propagation, a considerable amount of work was being done in the field. The field studies showed the following characteristics: (i) the fault trace on the surface was not a single continuous line but made up of many strands which showed en-echelon behavior, bifurcation, etc.; (ii) unequal slip across the length of the fault trace; and (iii) a complicated slip pattern which is more often than not made of both strike and dip components. In addition to the field studies, it was found that for some earthquakes the pattern of seismic activity after the main shock was limited to certain regions of the fault plane. The hypothesis put forward was that in the slipped regions there were no aftershocks and that they were confined to regions where the slip was constrained, say by the presence of stronger materials on the fault plane (Ref. 6). Also analysis of some observed earthquake records shows that they are made up of more than one event separated in time and space on the fault plane (Ref. 7). These facts seem to indicate that the faulting process is more heterogeneous than it was originally modeled. Further insight was provided by experiments done in the laboratory with rock specimen as well as on rubber models, which indicate that the faulting process can be best described as a slip-lock mechanism.

At this stage it may be worthwhile to pay attention to the mechanisms responsible for the generation of high-frequency wave motions. Madariaga (Ref. 8) showed that high-frequency motions are produced as a result of abrupt changes in the rupture velocity of the crack front. If this is the case, then an inhomogeneity on the fault plane which leads to sudden changes in the rupture velocity is a source of high-frequency energy. It is quite evident that there are many factors which can vary across the fault plane, for instance pre-existing tectonic stress, frictional stress, material strength, presence of inclusions, geometrical obstacles such as bends, twists, etc. In the light of Madariaga's hypothesis, a randomized rupture propagation model can be viewed as arbitrarily enforcing changes in rupture velocity in space and time which then is responsible for the complicated pattern of arrival of high frequency wave components.

The above discussion would indicate that a purely deterministic solution for acceleration is not feasible and therefore we will have to incorporate probabilistic methods. A recent model proposed by Gusev (Ref. 9) illustrates such a procedure. Gusev's model and models similar to his are based on one or more of the following assumptions:
1. the earthquake source is made up of multiple subsources,
2. the subsources are smooth and a kinematic model for the subsources are specified,
3. the size distribution of the subsources is specified, e.g., uniform, power law, etc.,
4. the space-time distribution of the subsources is specified--in some models the sources have been taken as non-overlapping while in others they could be overlapping, and
5. the radiation at a receiver station is the sum of the radiation from each of the subsources and typically the radiation is calculated using the far-field S-wave term for a homogeneous, isotropic, linear, elastic, unbounded medium.

The above model assumes that the complexity of the observed records arise from the source complexity. It does not include P-wave and surface wave

contributions. The practice of not including P-wave is on the assumption that the energy partition at the source favors the excitation of S-waves. In addition empirical observations, with the exception of some anomalous records, show that the energetic motion in the horizontal acceleration records takes place after the arrival of S-waves. Models like the one proposed above provide estimates of the ground motion during the interval of the direct S-wave arrival, however, as this is the time window during which the peak value occurs for most records, these models have the potential of estimating peak values. At the same time care must be taken in interpreting the results of such models as these models are based on average conditions for each subsource and are therefore average estimates for the total rupture. For instance the effect of directivity on high-frequency motion is lost as the azimuthal variation is usually averaged for each subsource so that the sum of the subsources also represents an average value. In addition these models do not take into account the local site effect and therefore their use should be limited to bedrock sites. Also, one needs to be careful in the near field as the direct P-waves and direct S-waves may not be clearly separated due to contributions coming from different points on the fault and therefore it remains to be seen how estimates using only the far-field S-wave term will compare with actual values.

A different approach of estimating the time history and/or spectra of the ground acceleration due to a big rupture event is by the use of aftershock records as Green's functions (Ref. 10). The great advantage of using aftershock records as Green's functions is that these records are the result of convolution of the source, the intervening medium and the local site effect. Assuming aftershocks as events which are characteristic of the sub-events which consititute the main event, the ground motion due to the main event can be obtained by a properly weighted sum of delayed aftershock records. The factors to be considered in the use of aftershock records as Green's functions are: (i) the type of faulting of the main event vis-a-vis that of the aftershock, (ii) the number of aftershock records required to simulate the main event, and (iii) the effect of varying hypocentral depth and varying epicentral distance. At this stage we need more experience in dealing with the last issue, however this method appears to be quite promising and the civil engineering community should make more use of it.

Another method which has been used by some researchers studying the spectra of ground acceleration is the Brune model (Ref. 11). Brune's model gives a description of the spectra of S-waves in a displacement record in terms of (i) a low frequency asymptote and (ii) a spectral decay at higher frequencies at some rate above a certain frequency. Knowing the displacement spectra, the acceleration spectra can be calculated using Eq. 1. Brune's model is based on some very simplifyied assumptions, even then it does explain the low frequency behavior of acceleration records, however,the rate of spectral decay and the corner frequency, see Fig. 1, is difficult to interpret. Also using the entire acceleration record, which is made up of P-waves and surface waves in addition to S-waves, makes any interpretation according to Brune's model highly untenable.

ENGINEERING CHARACTERIZATION

The ground motion at a receiver station is the manifestation of the potential energy release at the source. The amount of potential energy transformed

into kinetic energy during rupture of the finite source is a finite quantity and therefore at the receiver station, the motion of the ground is a transient. The acceleration record of the ground motion has been conventionally broken up into three regions: (1) the initial build up, (2) the strong motion, and (3) the decay. A qualitative description of the three phases in the acceleration record can be made.

The initial build up is composed primarily of faster travelling P-waves and is low in amplitude and high in frequency. The duration of this time interval is given by $T_s - T_p$, where T_s = S-wave arrival time from the hypocenter, and T_p = P-wave arrival time from the hypocenter. The strong motion usually starts with the arrival of direct S-waves and during the arrival of direct S-waves, the motion is fairly strong and quite high in frequency. The length of the direct S-wave time window can be approximated by the duration of rupture at the earthquake source. Depending on the distance to the source, the hypocentral depth and the local site conditions the direct S-waves are followed by body waves arriving from multiple ray paths and surface waves. The length of the time window during which surface waves are important is difficult to estimate. The amplitudes of the surface waves are medium to high, and the frequencies associated with them are lower than that for body waves. This part of the record, the strong motion phase, has traditionally been of most interest to the civil community. After the strong part of the record there is a decay portion which is composed primarily of coda of P- and S-waves and could also conceivably have contributions from the free vibrations of the soil layer at the site. Seismologists have studied the coda of the ground acceleration and Rautian and Khaltarin (Ref. 12) show how the coda can be used to study the seismic source spectrum.

As discussed above, the acceleration time history is a non-stationary process with both amplitude and frequency content varying with time. This is true even if we restrict ourselves to the strong motion phase. As non-stationarity is a negative concept, it is not a straightforward process to characterize a non-stationary time series, more so when there is just one record available. Out of necessity we have to do a short time analysis with the selection of the window length such that the properties vary slowly over the time window. At the same time we have to contend with the conflicting demand of frequency resolution, so that the choice of window length represents a compromise between time and frequency resolution. A description of window length and shapes with emphasis on their use in obtaining short-time windowed spectra can be found in Ref. 13.

Quite a few researchers have examined the non-stationarity in the acceleration records by using the so-called physical spectrum. Physical spectrum as defined by Mark (Ref. 14) is given by Eq. 2:

$$P_{xx}(f,t) = E[F_w^*, F_w]$$

(2)

where $$F_w(f,t) = \int_{-\infty}^{\infty} w(t - s) \, a(s) \, \exp(-2\pi jfs)ds$$

From the above equation, it is clear that the physical spectrum is in fact a windowed spectra of the original record. Care must be taken in using Eq. 2 to make sure that the original record $a(t)$ is sampled in such a way that the representation in terms of time and frequency is an unbiased representation.

Hoshiya et al. (Ref. 15) used this type of spectra and then estimated $P_{xx}(f,t)$ by the moment spectral method. This method of estimation assumes that $P_{xx}(f,t)$ is a Gaussian function in f, centered about some center frequency $f_1(t)$ and has a dispersion $f_s(t)$. The area under the Gaussian function when integrated over all frequencies is a function of t, $\alpha_0(t)$ which is taken as a measure of the localized mean square value. Hoshiya et al. parameterize $f_1(t)$, $f_s(t)$ and $\alpha_0(t)$ by some functional relation; the parameters of this function are then regressed on magnitude and distance.

With a technique similar to the one used by Hoshiya et al. but instead of using a short-time Fourier analysis then integrating the spectras, the authors are investigating the use of time domain measurements to get estimates of the local mean square value, central frequency, and band width over short time segments of the acceleration record. This time domain approach is similar in concept to the one used by Saragoni and Hart (Ref. 16). A consistent method to select time windows such that the process can be regarded as stationary, or almost stationary, is also being examined.

Other approaches have been used to study the non-stationarity in the acceleration records. These methods have essentially been developed to generate acceleration time histories which on the average exhibit the same non-stationary characteristics as the available earthquake data. We should also make attempts to relate in a quantitative manner the parameters of the non-stationary model to the physics of the rupture process but at this stage this appears to be a difficult task.

IMPORTANCE OF THE PHASE CONTENT IN EARTHQUAKE RECORDS

In most work done in simulating acceleration time histories, the phase has been as a matter of fact taken to be uniformly distributed in the range 0 to 2π. Given a spectral magnitude, stationary time series are then generated by the method of random phasings.

We will investigate the effect of taking into account the phase in reconstructing a time series. As pointed out by Ohsaki (Ref. 17), reconstructing a time series using the phase of an original signal and unit spectral magnitude for all frequencies preserved many of the features of the original signal. Ohsaki noted that the time series using the phase information and unit magnitude function differed from the original record in only that the reconstructed signal showed excessive magnification of high frequencies. This is the result of whitening the magnitude spectral, by making it equal to unity for all frequencies, while in real life the magnitude function shows a decay at high frequencies. The importance of phase in other signals has also been examined by Oppenheim and Lim (Ref. 18), who show by carrying out phase-only reconstructions and magnitude-only reconstructions that the phase-only reconstructions preserve the feature of the original signal better than magnitude-only reconstructions.

This property of phase reconstruction can then be used to generate data-based non-stationarity. The steps are outlined below:
1) calculate the phase associated with the given earthquake record,
2) use a magnitude function obtained from a seismological investigation as detailed in the early part of this paper or use an

average spectral magnitude obtained from empirical relations regressed on magnitude, distance, local site condition, etc.

3) combine 2 and 1 to generate non-stationary acceleration records, and

4) achieve ensemble generation by perturbing the magnitude function about its mean value.

A suggestion similar to this idea of using a phase spectrum from another earthquake record had been made by Bolt (Ref. 19).

CONCLUSION

Varying methods of developing magnitude functions were investigated and a method of combining the magnitude function with an appropriate phase spectrum was suggested to simulate non-stationary acceleration time histories.

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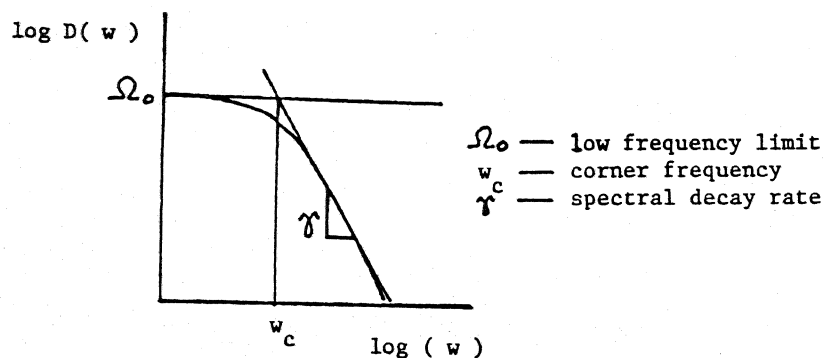
Figure 1. Brune's model.