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THE STICK-SLIP MOTION AS A SIMPLIFIED MODEL FOR THE SIMULATION OF SEISMIC EXCITATION

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ABSTRACT

The variable most commonly used to describe the earthquake strength is its magnitude, although its shortcomings are well-known. The major deficiencies of the magnitude as a strength parameter appear when attemping to describe the motion in the epicentral area. The feasibility of using the rupture area and the associated mean stress-drop, rather than magnitude, to characterize the *size* of the earthquake is herein explored and further justified by results obtained using the stick-slip model, which has also recently been proposed as adequate to simulate seismic motions.

KEY WORDS

SEISMIC MOTION, STICK-SLIP, PEAK ACCELERATION, MAGNITUDE, STRESS-DROP, RUPTURE AREA, RESPONSE SPECTRA.

INTRODUCTION

Most studies of seismic risk make use of the earthquake magnitude M to define the size of seismic events. For example, the magnitude is often introduced in so-called attenuation equations, aimed at the prediction of peak accelerations or velocities in terms of the epicentral, or hypocentral distances. Although the approach, on account of its simplicity, is convenient for engineering purposes, it is definitely not aplicable in the vicinity of the causative fault, where a number of important physical quantities such as deformation energy, stress-drop, dimension and geometry of the fault should be accounted for. In fact, more than two decades ago Trifunac (1973) remarked that the peak acceleration associated with high frequency components of the excitation should not be correlated with the magnitude, observing at the same time that, near the fault, the size of the fracture area looses significance.

In view of the preceding considerations, Riera, Scherer and Nanni (1986) explored the possibility of resorting to two parameters to describe the earthquake strength, suggesting that the rupture area A and the associated mean stress-drop $\Delta\sigma$ constitute an appealing choice. Riera and Doz (1991) further explore the idea, stressing the importance of the geometry of the problem in any attempt to predict, for engineering purposes, earthquake excitation at a site.

In fact, the origin of seismic motions is atributted to a process of faulting and fracture and/or to sudden relative movement of big portions of rock, caused by a state of stress that varies very slowly with time. As discussed by Doz and Riera (1985), it is clear that progress in the understanding of rupture phenomena in solids, like fracture propagation and fracture induced vibrations, will contribute to explain and eventually quantify different observed aspects of seismic motion. Initially, the authors (1985) explored the possibility of modeling earthquakes as mode II (shear) fracture processes, concluding that, rather than fracture in shear, the source mechanism involves sliding with friction, in a process known in mechanics of friction as stick and slide motion. A numerical model was then used to predict the motion of an analog block sliding along a rigid surface.

The results of a series of numerical simulations show that the rupture area and the mean stress-drop may be adequate choices to define seismic events. For instance, in the near field the spectral amplitudes depend fundamentally on $\Delta\sigma$. It has been suggested by Papageorgiou and Aki (1985) that there is a linear relationship between peak ground acceleration and stress-drop, which is confirmed by the stick and slip model. The shortcomings of using the magnitude as the only earthquake strength parameter is dramatically illustrated by the recent 1995 Great Hanshin earthquake records in Kobe which, to the authors knowledge, cannot be predicted by any expression based solely on the magnitude. These ideas are further discussed in this paper, and illustrated with an applications to the Great Hanshin earthquake.

EMPIRICAL EQUATIONS FOR RESPONSE SPECTRA

As an illustration of the feasibility of using the rupture area and the mean stress-drop for the prediction of earthquake motions, the following equations obtained by the authors (1991) are given:

* for intra-plate earthquakes (mean $\Delta\sigma = 100$ bars)

$$S_{ao} = 59.93 A^{0.34}\left(e^{-1.17T} A^{0.098T} + 494 T^{2.02} e^{-10.6T}\right) \tag{1}$$

$$\Phi = \frac{R^{(0.5e^{-1.1f}-1)}}{1 + 0.408 A^{0.29} \ln R} \tag{2}$$

* for inter-plate earthquakes (mean $\Delta\sigma = 60$ bars)

$$S_{ao} = 44.32 A^{0.25}\left(e^{-1.22T} A^{0.071T} + 494 T^{2.02} e^{-10.6T}\right) \tag{3}$$

$$\Phi = \frac{R^{(0.5e^{-1.1f}-1)}}{1+0.314A^{0.21}\ln R} \tag{4}$$

with the limitation R > 5Km. S_{ao} represent the source acceleration spectra and ϕ is an attenuation function that describes the decay rate of the spectral amplitude with distance from the source. T denotes the spectra period (s) and f = 1/T the frequency (Hz). When energy dissipation due to hysteretic damping or internal friction are not considered, the attenuation function can be expressed as:

$$\Phi = R^{(0.5e^{-1.1f}-1)} \tag{5}$$

which, for high frequencies (f > 5 Hz) approaches the decay rate for body waves (R^{-1}) and, for low frequencies (f < 1 Hz), approaches the decay rate of surface waves ($R^{-0.5}$). It is also well-known that the attenuation law for peak acceleration in the near-field is not similar to that in the far-field.. In the near field, the spectral amplitudes depend fundamentally on the stress-drop $\Delta\sigma$. It has been suggested by Papageorgiou and Aki (1985) that there is a linear relationship between peak ground acceleration and stress-drop, i.e.:

$$ZPGA \approx 0.01\Delta\sigma \tag{6}$$

with ZPGA in g's and $\Delta\sigma$ in bars. The linear relation (6) is a direct consequence of the hypotheses of material linearity. The proportionality constant was proposed by Riera and Doz (1991).

It is important to note that the parameters of equations (1) and (3), which characterize intra- or inter-plate earthquakes, depend on the stress-drop. The expected values calculated by Kanamori & Anderson (1975) indicate that $\Delta\sigma$ approches 100 bars in intra- and 60 bars in inter-plate earthquakes. Since the differences between expected values of the stress-drop in inter- and intra-plate earthquakes was found by Riera 'et al' (1986) to be statistically significant, different prediction equations result for each type of earthquake.

Taking into account the equations just defined, particularized for T = 0, it is possible to calculate the peak acceleration in rock, resulting, for intra-plate earthquakes:

$$(ZPGA)_o = \frac{59.93A^{0.34}R^{-1}}{1+0.408A^{0.29}\ln R} \tag{7}$$

and, for inter-plate earthquake:

$$(ZPGA)_o = \frac{44.32 A^{0.25} R^{-1}}{1+0.314 A^{0.21} \ln R} \tag{8}$$

with A in $10^3 Km^2$ and R in Km, $(ZPGA)_o$ results in $m/_{s^2}$. Taking into account that when $R \rightarrow 0$ equation (6) should substitute equations (7) or (8), the authors suggest a combination of these expressions in a law valid in the whole field: (Riera and Doz, 1991)

$$\frac{1}{a_{max}} = \frac{1}{C_1} + \frac{1}{C_1 + C_2} \tag{9}$$

where C_1 represents the lower value and C_2 the higher value between ZPGA and $(ZPGA)_o$. If the assumption represented by eq. (6) is extented to the entire spectrum frequency range, then eq. (9) may also be used to generate acceleration and pseudovelocity spectra.

Now, a complete law of attenuation valid in the whole field is obtained, based on the rupture area A, the distance to the source R and the stress-drop $\Delta\sigma$, factors that may be easily characterized in risk studies.

THE NUMERICAL MODEL: SLIDING WITH FRICTION

A numerical model has been developed based on the representation of earthquakes as the spontaneous stick-slip motion along the interface between the fault surfaces in contact. In fact, the stick-slip mechanism is considered to be the most adequate explanation of the origin of seismic motions. Fracture propagation in crystalline rock in Fracture Mode II is not considered feasible (Doz, 1995). Thus, as solids rupture, microcracks may give rise to unstable fracture propagation in Mode I, while sliding with friction along preexistent discontinuity surfaces may also occurs (Doz and Riera, 1995).

The model used in the numerical experiments consists of an homogeneous, prismatic block that lies on a rigid horizontal surface, subjected to gravity loads and to a specified slow horizontal motion of a point on its left boundary. The interface constitutive relations are based on the assumption that the simple dry friction criterium applies, that is, the interface shear cannot exceed the normal stress times a friction coefficient. At low shear stress levels along the interface surface, stresses increase monotonically without relative displacement between adjacent points on the interface. When the interface shear stress at a point exceeds the local shear strength, slip at a node occurs, which eventually propagates to neighbouring nodes,

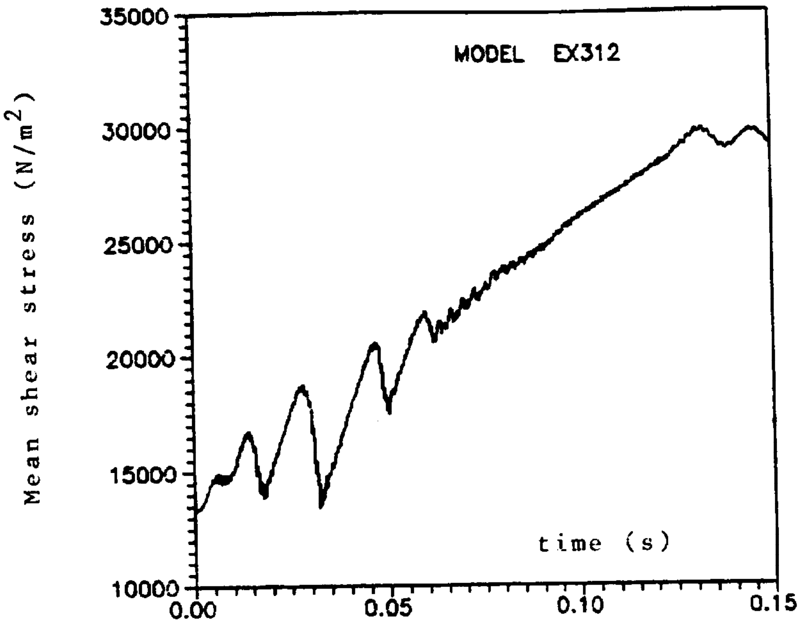

Fig 1. Evolution of total shear with time, showing four seismic events with pronounced mean stress drop.

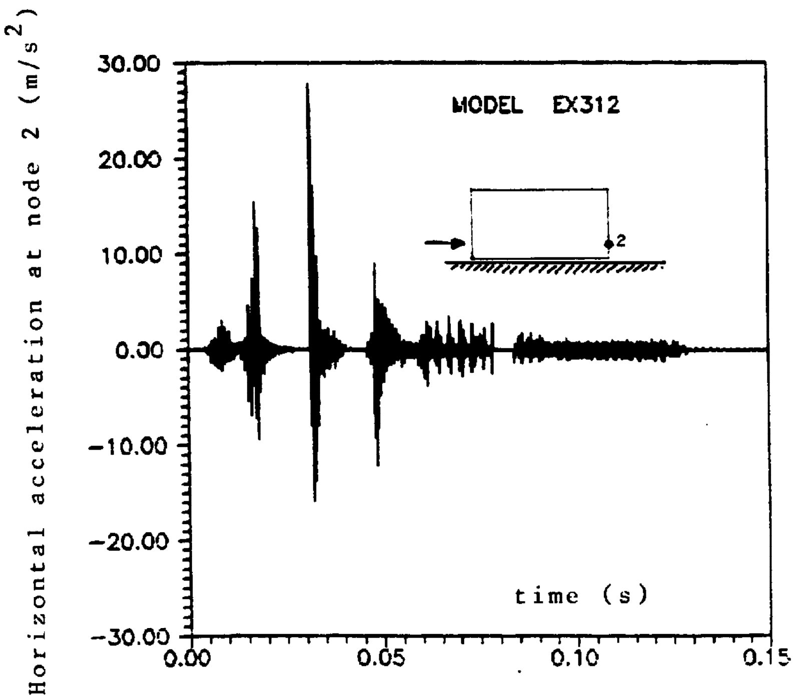

Fig 2. Accelerations parallel to the "fault", in a neighbouring point. The acceleration time-histories for each of the four events indicated in Fig 1 can be clearly identified.

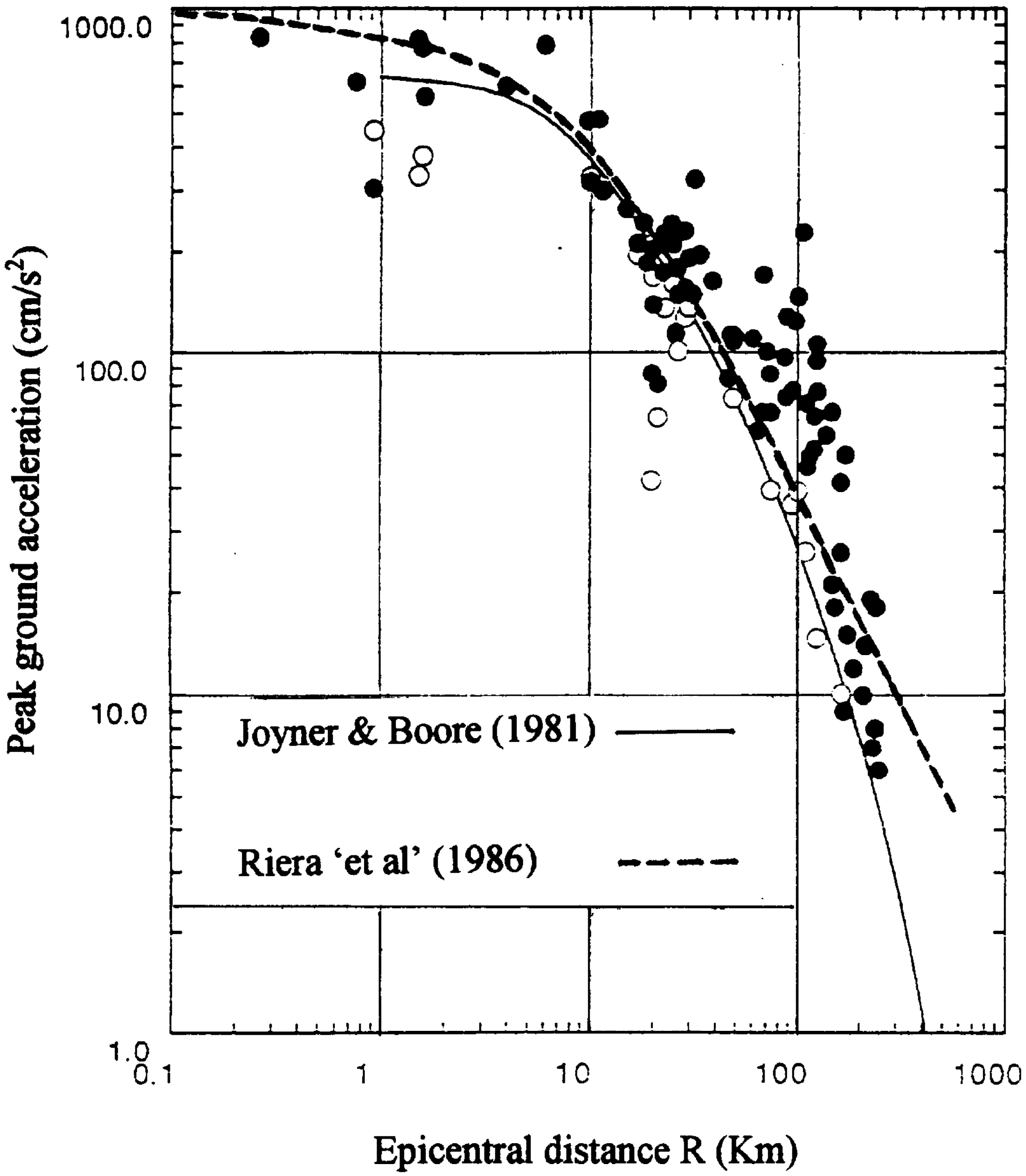

Fig.3 Attenuation Law for peak ground acceleration for Great Hanshin earthquake (Measured values after Shibata, 1995)

causing a sudden stress-drop associated with an important displacement (Fig. 1). That unstable slip phenomena has been observed in many types of rock and metals, as well as in rubber foam (Brune 'et al', 1993). In the numerical studies it was observed that the stick-slip phenomenon with large stress drops only occurs when the friction coefficient is equal or larger then.

The mean stress drop associated to each seismic event, as well as the vibrations induced throughout the block are computed. The acceleration time history at a point near the "fault"plane is shown in Fig. 2. It is verified that the peak accelerations close to the rupture surface increase linearly with the mean stress-drop, confirming one of the hypothesis proposed in this paper to define seismic motions in terms of the mean shear stress-drop and rupture area.

APPLICATIONS

One of the advantages of resorting to the rupture area and mean stress drop to characterize the seismic event is that both have an immediate and clear physical meaning and should then appeal to engineers. In addition, in the development and calibration of realistic models, such as solids experiencing fracture and/or slip with friction, as described in the preceding section, with resulting stick and slip motion, both factors can be clearly identified, while the magnitude would be much more difficult to determine.

The magnitude of the recent Great Hanshin earthquake (1995) was estimated as 7.2. For intra-plate earthquakes, Riera 'et al' (1986) established, using Kanamori and Anderson (1975) data base, the regression equation:

$$M = 7.078 + 0.769 \log A \tag{10}$$

from which it may be inferred that, with $M = 7.2$, $A = 1500\ \mathrm{Km}^2$. This area is compatible with an estimate based on the distribution of slip, according to Shibata (1995), from which a slightly smaller area may be inferred. Then, taken $\Delta\sigma$ equal to the mean stress drop for intra-plate earthquakes, eq. (6) leads to ZPGA = 1g, while the source peak acceleration, at long distance from the fault, may be obtained from eq (7). Finally, equation (9) permits obtaining an attenuation curve valid in the entire field, which is compared in Fig. 3 with measured values of the peak acceleration and with Joyner and Boore (1981) predictions, furnished by Shibata (1995). Obviously, a rather large scatter for unclassified samples in terms of soil properties may be expected. The correlation, nevertheless, is quite satisfactory, fitting the data better than the Joyner & Boore (1981) relation.

CONCLUSIONS

It is quite clear that the effects of an earthquake cannot be closely predicted on the basis of the single measure of its size, like its magnitude, except at locations removed from the epicentral area, which has little engineering interest. Using two parameters appears to be a need in engineering applications in which a complete description of the excitation is required, as for instance in nuclear power plant analysis and design.

The rupture area and the associated mean stress-drop are two possible quantities that may be used in conjunction for the same purpose with many advantages. The adequacy of the proposal should nevertheless be carefully evaluated. The progress that took place in recent years in the prediction of rupture phenomena in solids, suggests that the evaluation of seismic motions from a complete model of the initial conditions along the causative fault should be given special considerations in the plannification of research for future seismic risk studies.

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