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Ground motions from intraplate earthquakes

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ABSTRACT: The needs within the petroleum industry for more reliable wave attenuation relations for the intraplate Norwegian continental shelf, where the seismicity is moderate and where strong motion records are rare, has led to an effort in which large amounts of observed data from seismometers have been used for calibration of models for stochastic (random vibration) predictions of the ground motions. Large amounts of data have been used in this respect in establishing M_L magnitudes, $M_L - M_S$ relations, seismic moments, moment-magnitude relations, corner frequencies, stress drop, anelastic attenuation and geometrical spreading. When combined with derived relations for ground motion duration these parameters have provided a reliable basis for ground motion predictions using stochastic ω-square models. The prediction models are derived both for a constant stress drop of 50 bars and for increasing stress drop (with magnitude), giving predicted ground motions that agree quite well with observations over a wide range of magnitudes (M_L 2-5) and frequencies (0.2-10 Hz). The resulting attenuation models have been tested and used in realistic assessments of earthquake hazard for sites at the Norwegian continental shelf, and should be applicable also to other intraplate environments where seismotectonic conditions are similar.

1 INTRODUCTION

The Norwegian continental shelf (NCS) is an area with moderate seismicity (Bungum et al., 1991). With the development of large hydrocarbon fields at NCS the offshore operators and the authorities (Norwegian Petroleum Directorate, 1991) have agreed that offshore platforms shall be designed to withstand, without collapse, environmental loads with an annual probability of occurrence of 10^{-4}. This safety level is selected to safeguard personnel, environment and investments, and the decision has prompted industry and authorities to jointly undertake studies (e.g., Selnes et al., 1983; Bungum and Selnes, 1988) to identify the earthquake hazard to offshore platforms as well as to onshore sites such as oil terminals and processing plants.

It is well known that some of the larger uncertainties in earthquake hazard analyses are caused by uncertainties in seismic wave attenuation, and in particular so for intraplate areas where strong motion data usually are quite rare. The present work (NORSAR & Risk Engineering, Inc., 1991) has been aimed in this respect towards developing new and more reliable relations for NCS, using the calibrated-theoretical method of stochastic ω-square (random vibration) predictions. The results and parameters needed for this calibration have been possible to establish because of significant efforts within both seismological data acquisition and research in Norway during the last 20 years.

2 DESCRIPTION OF THE RANDOM-VIBRATION MODEL

The random-vibration (RV) model of earthquake ground motions uses Brune's (1970, 1971) spectrum, together with simple, yet physically sound, assumptions about geometric spreading and anelastic attenuation, to represent the Fourier amplitude of ground motion due to shear waves. Using this spectrum and the associated duration, one calculates the root-mean-square (rms) and peak amplitudes of ground response by assuming that the ground motion during the strong-shaking portion of an earthquake is a finite-duration segment of a gaussian random process. This model is attractive because it is based on seismological principles (yet it has few parameters, due to its highly simplified assumptions, because it follows a rigorous mathematical procedure to calculate time-domain amplitudes from Fourier amplitude and duration, and because it can predict virtually every measure of ground motion (e.g., acceleration, velocity, response spectra, seismograph response).

The RV method has been used extensively to predict ground motions in California (e.g., Hanks and McGuire, 1981; Boore, 1983; McGuire et al., 1984), in eastern North America (ENA; e.g., Boore and Atkinson, 1987; Toro and McGuire, 1987; McGuire et al., 1988; Boore and Joyner, 1991), and in other regions (Wong et al., 1990).

This method is particularly attractive for low-seismicity regions like ENA and NCS, where there are few or no strong-motion recordings from magnitudes and distances of engineering interest. Because significant extrapolation of the data is required, one is more confident in performing this extrapolation using a model with a strong theoretical justification. In addition, seismological studies and analogies with other regions provide additional data that can be used in the development of parameters for the RV model.

The RV model represents the Fourier spectrum of ground acceleration, in an arbitrary horizontal direction, in the form:

$$a(f) = \left(\frac{0.85M_0}{4\pi\rho\beta^3}\right)\left(\frac{(2\pi f)^2}{1+(f/f_0)^2}\right)G(r)e^{-\alpha(f,r)}H_{fmax}(f) \quad (1)$$

in which the factor of 0.85 includes the effects of average radiation pattern, free-surface amplification, and vectorial partition of energy, r is hypocentral distance, ρ is crustal density, β is shear-wave velocity at the seismic source, f_0 is the source corner frequency, and M_0 is the seismic moment ($M_0 = \mu\bar{u}A$, where μ is the crust's shear modulus, $\bar{u}$ is the average slip, and A is the rupture area). $G(r)$ represents geometric spreading, $e^{-\alpha(f,r)}$ represents the effect of anelastic attenuation, and $H_{fmax}(f)$ represent near-site attenuation at high frequencies.

The second paranthesis in the above equation describes the shape of the Brune acceleration spectrum, where f_0 is the corner frequency (where the acceleration spectrum changes from being proportional to f^2 to being proportional to f^0). The corner frequency is related to the stress-drop $\Delta\sigma$ through the relationship $f_0^3 = (\Delta\sigma\beta^3)/(8.44M_0)$ (Brune, 1970, 1971).

The variation of stress drop with seismic moment determines the variation of corner frequency with seismic moment. The latter is referred to as the source-scaling law.

Finally, the RV model requires specification of the ground-motion duration T, in order to calculate the power spectrum of ground acceleration. This power spectrum is then used to predict peak ground acceleration, peak ground velocity, response spectra, or seismograph response, using simple concepts of linear filtering and random-process theory (see Vanmarcke, 1976, or Boore, 1983).

Because the RV model uses seismic moment to quantify earthquake size, and earthquake catalogs use magnitude for this parameter, a relationship between these quantities must be assumed or established. This may be done using the RV model itself or using empirical data.

The most important parameters (or assumptions) in the RV model are the stress drop (and its dependence on seismic moment), the functional form of the geometric-attenuation term $G(r)$, the anelastic-attenuation term $\alpha(f,r)$, the near-site attenuation term $H_{fmax}(f)$, and the duration T.

3 DATA

For the purpose of this study an extensive data base of 1076 digital recordings at distances between 20 and 1600 km from 213 earthquakes with magnitudes up to M_L 5.2 was established. In addition, 153 analog seismograms from 45 larger historical earthquakes were collected from the seismological observatories in Uppsala and Bergen.

Following a quality and reliability analysis which removed around 25% of the data, the remaining digital records were processed in a way which resulted in the following output: (a) ground displacement (response corrected) noise spectra from a time window preceding the P_n arrival, (b) ground displacement L_g spectra, (c) ground acceleration L_g spectra, and (d) response spectra at 5% damping for the Lg phase, between 0.2 and 10 Hz.

For around 15% of the digital data and almost all of the analog data three-component records were available, and these data were used for analysis of ratios een components.

4 ESTIMATION OF RV MODEL PARAMETERS

The various parameters for the RV model were estimated using the data set described above, as well as from seismological investigations of this same data set. We also used insights from the application of the RV method in other regions.

Stress Drop and Source Scaling

Application of the RV model in numerous other regions (see references above) suggests that a constant stress drop of 100 bars (± a factor of 2) is consistent with observed ground motions over a wide range of magnitudes.

An investigation of the Fourier amplitude spectra of the Scandinavian records processed in this study (Kvamme et al., 1992, in preparation), suggests that stress drop increases with earthquake size. The stress drop for M_L 2.5 earthquakes ($M_0 = 10^{13}$ Joule) is 1 to 10 bars, whereas the stress drop for M_L 4.5 ($M_0 = 10^{16}$ Joule) is approximately 30 bars.

This trend of increasing stress drop may or may not be real. The corner frequencies inferred from L_g records of small, distant events may not represent the true source corner frequencies, as shown by Haar et al. (1986). Also, the high corner frequencies of small events may not be resolved due to the 10-Hz band limit of most records.

To represent this uncertainty on the interpretation of the results from Kvamme et al. (1992), we consider two alternative models. The first model has a constant stress drop of 50 bars (this value is based on the stress drops obtained by Kvamme et al. for the larger events, which have magnitudes near 5). The second model has increasing stress drop.

The parameters of the increasing stress drop model (i.e., the slope and intercept of the relationship between $\log M_0$ and $\log f_0$ were selected using nonlinear regression, where we minimized the residuals between observed and predicted spectral velocities. The resulting scaling law is shown in Fig. 1.

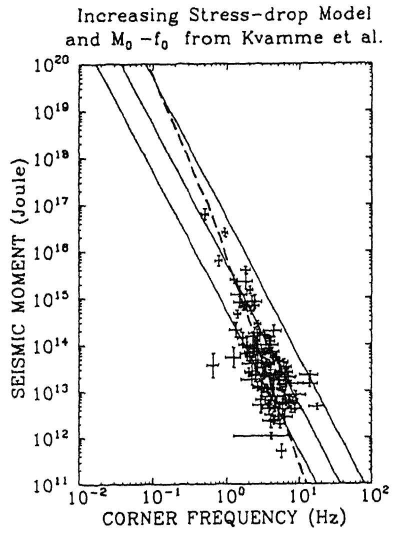

Fig. 1. Source scaling model with increasing stress drop: relationship between seismic moment and corner frequency (heavy dashed line). Also shown are seismic moments and corner frequencies obtained by Kvamme et al. (1992; with 1σ error bars), and the relationships corresponding to stress drops of 1, 10, and 100 bars (solid lines).

Geometric Spreading

We adopt the geometric spreading form (for Fourier amplitudes) proposed by Street et al. (1975; see also Herrmann and Kijko, 1983). This functional form considers the spreading term $G(r)$ in equation (1) for distances $r \leq r_0$ to be $1/r$, corresponding to spherical spreading of direct S waves, and for distances $r > r_0$ to be $1/\sqrt{rr_0}$, corresponding to cylindrical spreading of L_g waves (S waves trapped in the crustal waveguide). The recommended value for r_0 is 100 km. This functional form and value of r_0 have been used by numerous authors for ENA earthquakes and by Sereno et al. (1988) for Scandinavian earthquakes.

Duration

Herrmann (1985) proposed a distance-dependent duration for use in RV calculations. Herrmann's definition of duration accounts for the increased duration due to Lg wave propagation.

We used the records processed in this study to investigate the validity of this expression to NCS. We considered two definitions of duration. The definition by Vanmarcke and Lai (1980) uses the peak acceleration a_{max} and the total energy $I_0 = \int a^2(t)\,dt$ of the record, and is given by $T_{VL} = (2.74)^2 a^2_{max}$. The definition by Ou and Herrmann (1990); (we call this T_{5-75}) is given by the time interval between the instants when the cumulative energy reaches 5 and 75% of the total energy I_0.

Plots of duration vs. distance and duration/distance vs. distance show a linear dependence on distance, for all distances. These plots show a large scatter, particularly for T_{VL}.

Calculations (using both definitions of duration) indicates that Herrmann's (1985) expression for duration is applicable also to NCS.

Anelastic Attenuation

Anelastic attenuation is typically represented by a factor of the form $\alpha(f, r) = (\pi f r) / [\beta_c Q(f)]$, where f is the frequency, r is hypocentral distance, β_c is the average group velocity of L_g waves and $Q(f)$ is a material property known as the quality factor. We use $Q(f) = 465 f^{0.64}$, which was obtained by Kvamme et al. (1992). These results are reasonably consistent with other recent $Q(f)$ results from the same region (Sereno et al, 1988; Kvamme & Havskov, 1989; Hansen et al., 1989; Dahle et al., 1990) and with results obtained from ENA.

Near Site Attenuation

Near-site attenuation is important only for the prediction of peak ground acceleration or high-frequency (10 Hz) spectral velocity at short and moderate distances. Because no good data are available to study this effect, we use results from ENA. Following Toro and McGuire (1987), we represent near-site attenuation by a low-pass filter with frequency $f_{max} = 40$ Hz. This value is believed to be applicable to (on-shore) rock-site conditions in Norway.

5 RESULTS

Fig. 2 shows the relationship between the Scandinavian M_L magnitude (Alsaker et al., 1991) and seismic moment developed with the RV model (following the procedure by Hanks and Boore, 1984). Also shown are the magnitudes and seismic moments for the digital records in this study. This relationship is used to obtain the seismic moment associated with a certain magnitude, which is required for predicting ground motion for given magnitude and distance. Comparison of observed and predicted magnitude-moment relationships also serve as validation for the RV model and parameters.

Fig. 3 shows the observed and predicted spectral velocities at 5 Hz (5% damping, vertical component). Similar agreement was obtained for frequencies in the 0.2 to 10 Hz range (the number of 0.2- and 0.5-Hz data with acceptable signal/noise ratios is very small, though).

The RV model was also used to predict the amplitudes of analog seismograph records available from older events (magnitudes up to $M_S = 6.1$, distances 250 to

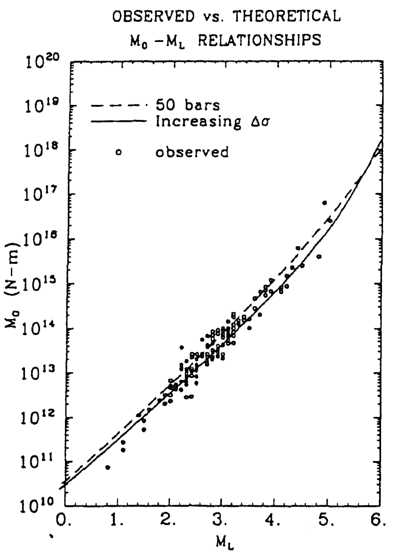

Fig. 2. Theoretical (RV-based) $M_0 - M_L$ relationships for a constant stress drop of 50 bars and for an increasing stress drop model as shown in Fig. 1. The small circles denote independent observations.

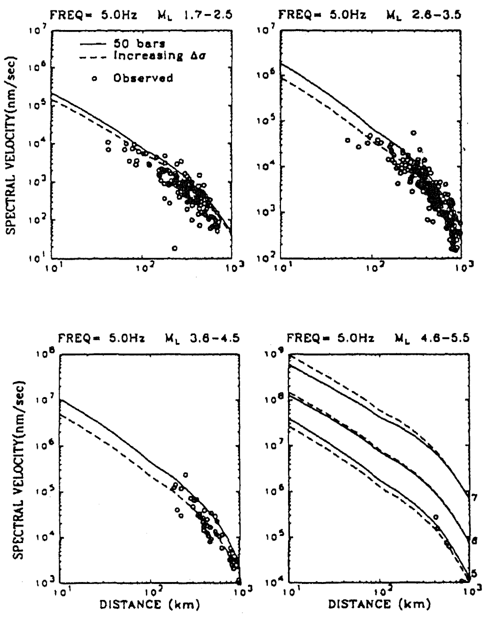

Fig. 3. Predicted spectral velocities at 5 Hz (5% damping) as compared to spectral velocities calculated from the digital records, for vertical motion. The data are scaled to the nearest integer magnitude for comparison to the predictions. The lower right panel also shows predictions for M_L 6 and 7.

2000 km). Comparisons with the observed amplitudes indicates overall agreement, although there is considerable scatter. These comparisons are important because they confirm the validity of the model for higher magnitudes.

For the sake of convenience in seismic-hazard calculations, attenuation equations were fit to the RV-model predictions for peak acceleration and spectral velocities between 0.1 and 10 Hz. Two sets of attenuation functions were generated, corresponding to the two stress-drop models. Fig. 4 shows in this respect predicted values for 1-Hz spectral velocity (5% damping, vertical component), and Fig. 5 similarly for peak ground acceleration. Note in particular the decrease in magnitude scaling with increasing frequency.

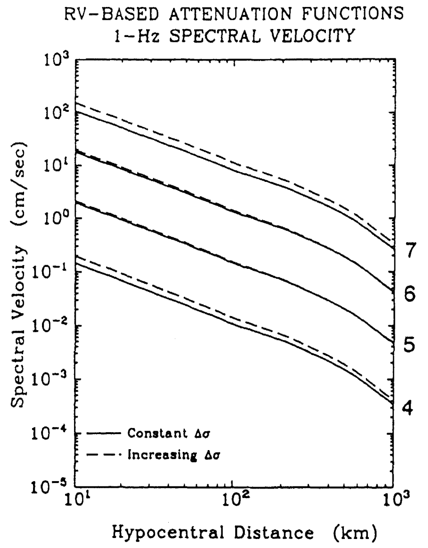

Fig. 4. RV-based predictions for 1-Hz spectral velocity, for 5% damping and for vertical motion. Results are shown for magnitudes (M_L) 4, 5, 6 and 7, for a constant stress drop (50 bars) and increasing stress drop model (cf. Fig. 1).

Applications

For the purpose of seismic hazard evaluations at NCS sites, these RV relations have been combined through appropriate weighting with attenuation relations based on empirical regressions of intraplate accelerometer and seismometer data (Dahle et al., 1992), and with RV relations published earlier for ENA (Boore and Atkinson, 1987; McGuire et al., 1988).

The resulting ground-motion amplitudes for an exceedance probability of 10^{-4}/year have changed little from earlier estimates, but the amplitudes for 10^{-2}/year are much lower than earlier estimates. The reason for this is that the ground motion predictions are comparable for the magnitudes (5.5-7) that contribute the

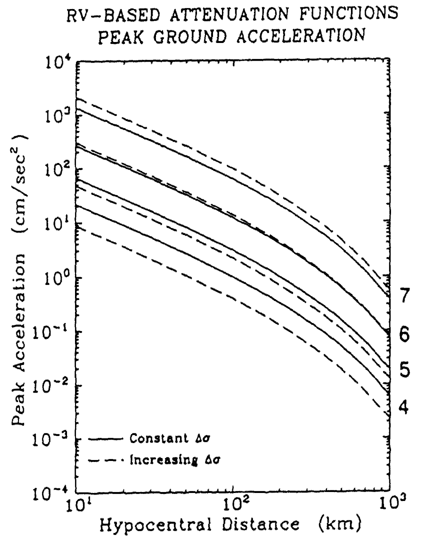

Fig. 5. RV-based predictions as in Fig. 4, but for peak ground acceleration.

most the 10-4/year hazard, while the ground motions from magnitudes (4-5.5) that contribute the most to the 10^{-2}/year hazard now are significantly reduced as a result of an increased magnitude scaling.

The results obtained in this study for the Norwegian continental margin areas should be applicable also to other intraplate areas where the seismotectonic conditions are similar. It is a common problem with most such regions that sufficient strong motion data are not available for independent development of reliable wave attenuation relations.

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