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A Site Specific Estimation of Fourier Amplitude Spectra — An Alternative to Standard Response Spectra

J. Taud-Turnovsky

Kraftwerk Union AG, Abteilung VRS 13, Postfach 3220, D-8520 Erlangen, Germany

Summary

The present method of safeguarding and designing a nuclear power plant is based, except in very unusual circumstances, on the use of standard response spectra together with an estimation of maximum acceleration and duration of strong motion. The maximum acceleration at a specific site is obtained from empiric relationships linking macroseismic intensity, distance,magnitude and occationally site conditions with acceleration. The duration of strong motion is defined differently by various authors and it's value is usually determined as a result of the author's experience in analysing seismograms and accelerograms. The standard response spectra were developed from an ensemble of accelerograms that represent a variety of seismologic, geologic and local soil conditions.

This paper discusses various shortfalls of the site independent technique outlined above. In particular, a review of peak acceleration as a measure of strong ground motion over the entire frequency band and amplitude range of engineering interest is presented. Further, the use of broad response spectra in areas of low to intermediate seismicity, subject only to local earthquakes, is questioned.

A method is outlined for determining site dependent Fourier amplitude spectra for use as input data to soil-structure interaction calculations in the frequency domain. The method is based on a direct multiplication of a crystalline basement acceleration density spectrum (Fourier spectrum) with the transfer function applicable to the particular site. The crystalline basement acceleration density spectrum is obtained from simple seismic source models (AKI /9/, BRUNE /10, 11/). The far field radiation emanating from such models is characterised by a long period level Ω_o proportional to the seismic moment M_o, a corner frequency f_o, proportional to source area and a high frequency spectral decay of the form $(f/f_o)^{-\gamma}$. The far field, high frequency shear radiation for the $\gamma = 2$ model in the presence of anelastic attenuation may be considered as band limited finite duration white noise in acceleration. Such an interpretation leads to a flat acceleration density crystalline basement spectrum. The synthetic spectra are tested against those from the 1978 Swabian Jura earthquake series in Germany.

1. Introduction

Since 1933, when the first strong motion records were obtained, study and analysis of the relationships linking maximum acceleration, earthquake magnitude, duration of strong ground motion, soil conditions and incurred damage have attracted much attention and are still today major areas of research. Due to only rudimentary knowledge concerning the source process and because of the parallel but rarely crossing paths of engineering and theoretical seismologists, there exist today literally scores of empiric relationships linking the above five. These relationships form today the basis of calculations, needless to say, of arguments and heated discussions, for the design of nuclear power plants against seismic loads.

With today's much better understanding of the seismic source and propagation processes, and in Blume's /1/ opinion, clear indications that installations with high safety requirements are designed with very conservative accelerations and procedures, there is not only sufficient knowledge available but also a need to update and improve the procedures for estimating the seismic input for safer design of nuclear power plants.

Specifically, there is accumulating evidence that peak acceleration and standard response spectra are inadequate in this context, particularly in areas subject only to local earthquakes with intermediate magnitudes. This paper attempts firstly, to give the main reasons for the inadequacy and secondly, to outline the principles toward a more realistic design practice.

The method is based on the awareness that a free-field spectrum is the product of a source spectrum and the transfer function of that particular geologic sequence along the propagation path between source and observer (site). The surface free-field spectrum contains therefore the combined effects of a site independent earthquake source and a site dependent transfer function. At any particular site therefore, a free-field Fourier amplitude spectrum of acceleration may be obtained by use of suitable source and propagation path models.

There is nothing new in the method to be discussed except perhaps a transfer of knowledge from theoretical to engineering seismology, as the same principles have formed the basis of source and crustal studies over the past few decades. Already in 1972, Trifunac wrote, "modelling through theoretical spectra offers a better and more rational basis for future predictions of strong ground motion, far more realistic than presently used methods, which are mainly based on the statistics of the magnitude scale", /2/.

Theory and observation are tested against one another using acceleration records from the 1978 Swabian Jura earthquake series in the Federal Republic of Germany. Practical application is then discussed with particular reference to Germany.

Finally, the question of obtaining theoretical spectra comparable to single degree of freedom response spectra is addressed, bearing in mind the particular needs of nuclear engineering seismologists.

2. Peak acceleration and standard response spectra

There is growing support for the belief (though it is difficult to prove) that the large peak accelerations (> 0.1 g) at short distances ($\simeq 10$ km) are expressions of localized dynamic stress differences on rupture surfaces (Hanks & Johnson, /3/, Hanks /4/).

These localized stress differences are much greater than the average earthquake stress drops and give rise to high frequency pulses of large amplitude and duration much shorter than that of the entire rupture. These are recorded by accelerographs at close distances as the peak accelerations. This interpretation is supported by the fact that recent studies have shown that peak acceleration is practically independent of magnitude ($M \gtrsim 4.5$) at short distances (various authors /3, 5 - 7/).

The peak acceleration cannot therefore be a uniformly valid measure of strong ground motion over the entire frequency band and amplitude range of engineering interest. Neither can the peak acceleration be a measure of the gross source properties nor of potentially damaging earthquakes ($M \gtrsim 4.5$).

Scaling of response spectra by the use of peak accelerations is in fact quite contrary to this physical interpretation. As a consequence, it is very difficult to quantify the safety margins involved, with any degree of accuracy. Much more predictable and realistic would be scaling of the response spectra in the low frequency range (2 $\sim$ 8 Hz), as a better representation of the overall energy source, particularly for earthquakes of intermediate magnitude, would be achieved. Furthermore, scaling would occur at a frequency close to that of the resonant frequency of the principal engineering structure of interest.

Another matter of interest to designers of installations with high safety requirements in central Europe is the use of standard response spectra which have their origin in non-european physical situations. Whereas the use of "broad-band" standard response spectra can very well be justified in many parts of the world, no such justification can be found for use in central Europe and in particular in Germany. Here, ground motions with sufficient amplitude and in the frequency range of interest to the nuclear power plant designer are to be expected only from local earthquakes of intermediate magnitude ($M \lesssim 6.0$). The differences to design can only be imagined when one compares the use of standard and typical local earthquake response spectra as in fig. 1. It is quite evident that use of the standard spectra would assume the presence of a large amount of low frequency energy that in reality cannot be expected in areas subject only to local seismicity of an intermediate level.

3. Model estimates

The physical model used for the estimation of the motion characteristics at the surface is shown in fig. 2. The earthquake source lies within crystalline (uniform, elastic and isotropic) basement rocks below a horizontally layered sedimentary sequence. It is assumed that the most energetic and potentially damaging part of the seismic radiation is composed of direct upward propagating horizontal shear waves (SH).

The synthetic free-field Fourier amplitude spectrum $F(\omega)$ is obtained from the seismic source spectrum $S(\omega)$ and the transfer function $T(\omega)$ of the medium between source and observer.

$$F(\omega) = S(\omega) \cdot T(\omega) \qquad (1)$$

$T(\omega)$ may further be split into two parts due to the separate effects of media below and above the sedimentary base.

$$T(\omega) = T_c(\omega) \; . \; T_s(\omega) \qquad (2)$$

$T_c(\omega)$ represents the transfer function of crystalline basement rock while $T_s(\omega)$ must include all the influences of the sedimentary layered medium. This division of the transfer function leads to the concept of a crystalline basement rock spectrum $K(\omega)$ which characterizes the motion at the top of the basement rock below the sedimentary sequence.

$$K(\omega) = S(\omega) \; . \; T_c(\omega) \qquad (3)$$

$$\text{thus} \quad F(\omega) = K(\omega) \; . \; T_s(\omega) \qquad (4)$$

$K(\omega)$ may then be considered as the input to the sedimentary sequence below the site of interest for the synthetic calculation of $F(\omega)$.

The seismic source spectral properties have been adequately modelled for the purposes of engineering seismology, through the well known work of Haskell, Aki and Brune /8 - 11/. The salient features of the model shown in fig. 3a are firstly, a low frequency constant amplitude level Ω_o and secondly, a high frequency decay as $f^{-\gamma}$ where γ lies between 1.0 and 3.0. Hanks /4/, argues that the $\gamma = 2$ model is the one generally applicable to crustal earthquakes. The low and high frequency parts of the source Fourier amplitude spectrum of displacement $\tilde{u}(f)$ are separated by a corner frequency f_o, related to source size, rupture and wave velocities. The Fourier amplitude spectrum of acceleration $\tilde{a}(f)$ can be obtained from $\tilde{u}(f)$ by multiplying with $(2\pi f)^2$, leading to the typical spectrum shown in fig. 3b. When distance R is taken to be the shear wave travel path from the source to the top of the crystalline basement rock, and including attenuation effects, then fig. 3b may be likened to $K(\omega)$.

The explicit derivation of $F(\omega)$ is as follows:

$$\tilde{u}(f) = \Omega_o \; . \; \frac{1}{(1 + f^2/f_o^2)} \qquad (5)$$

$$\text{and} \quad \tilde{a}(f) = (2\pi f)^2 \; . \; \Omega_o \; . \; \frac{1}{(1 + f^2/f_o^2)} \qquad (6)$$

where the reciprocal of $(1 + f^2/f_o^2)$ represents the behaviour of $\tilde{u}(f)$ at high frequencies. The low frequency level is given by:

$$\Omega_o = \frac{M_o}{4\pi \rho R \beta^3} \; . \; R_{\vartheta\varphi} \qquad (7)$$

where M_o is seismic moment, $R_{\vartheta\varphi}$ is the radiation pattern of shear excitation, ρ is density and β is shear wave velocity. $\tilde{a}(f)$ may be considered to be the source spectrum $S(\omega)$ at a distance R from the source. Assuming an elastic, uniform and isotropic crystalline basement rock, then $T_c(\omega)$ is the anelastic attenuation factor $\exp(-\pi fR/Q\beta)$ where Q is the specific attenuation, also known as the quality- or simply Q factor. Thus the Fourier amplitude spectrum of acceleration at the crystalline/sediment interface is :

$$K(\omega) = \frac{\pi M_o f^2_o}{\rho R \beta^3} \; . \; R_{\vartheta\varphi} \; . \; \frac{1}{(1 + f_o^2/f^2)} \; . \; \exp(-\pi fR/Q\beta) \qquad (8)$$

The well known expression for the transfer function of layered media applicable to the model of the sedimentary sequence, $T_s(\omega)$, is not reproduced because of space limitation, but is given in original form by Haskell /13/. Multiplication by $K(\omega)$ leads to the desired free-field Fourier amplitude spectrum of acceleration $F(\omega)$.

4. Theoretical spectra

Following the general theory outlined above, Scherbaum /12/ has synthesized $F(\omega)$ for a number of smaller aftershocks of the 1978 Swabian Jura earthquake. A very good fit has been achieved, as shown in fig. 4, certainly for the purposes of engineering seismology. Comparison of synthetic and real Fourier amplitude spectra for purposes of nuclear seismic engineering are appearing slowly in the literature. A very good paper on the subject was published by Hasegawa /14/ as early as 1974.

Space limitation does not allow a discussion of the sources of error in the method outlined, but an average theoretical Fourier spectrum can be imagined using a range of possible sediment layer parameters. Scherbaum /12/ shows such a model spectrum for the 1978 Swabian Jura main shock with a local magnitude of 5.7.

5. Response spectra

Response spectra are needed by the engineering seismologist for reasons that are sometimes very difficult to understand by outsiders to the field. One hears variously; they are needed to indicate the maximum acceleration and to calculate the maximum shear strain that a particular component must withstand, or, they are needed for the generation of particular time histories, which in turn must be used when dealing with non-linearities in soil-structure interaction analyses. Whatever the reasons, it seems as if the response spectrum is here to stay for a while yet.

A close mathematical approximation to the single degree of freedom response spectrum is the Fourier amplitude spectrum of acceleration $F(\omega)$ multiplied by $2\pi f$. A physical justification for the oft used mathematical "short cut" is difficult to find but is quite well discussed by Hasegawa /14/ and Housner /15/.

6. Discussion

It can be envisaged that the synthetic Fourier and response spectra based on realistic source and propagation models, contain more accurate amplitude/frequency information than standard response spectra. Certainly one would be able to asign confidence levels to the calculated spectra and one would not be defining the seismic input motion by the rather erratic peak acceleration.

This move away from standard response spectra seems to be justified where damage is only expected to occur because of local earthquakes of intermediate magnitude. Furthermore, the geologic substructure, in particular, the depth to the interface between sedimentary and crystalline (igneous and metamorphic) basement rocks is fairly well defined throughout the country. The present zonation of seismic risk in Germany could serve as a starting point for the definition of crystalline basement rock Fourier amplitude spectra of acceleration $K(\omega)$. The site dependent Fourier and/or response spectrum would be obtained by use of a specific $K(\omega)$ and a particular sedimentary sequence. The site specific spectrum so obtained could serve directly as input to the soil-structure interaction calculations.

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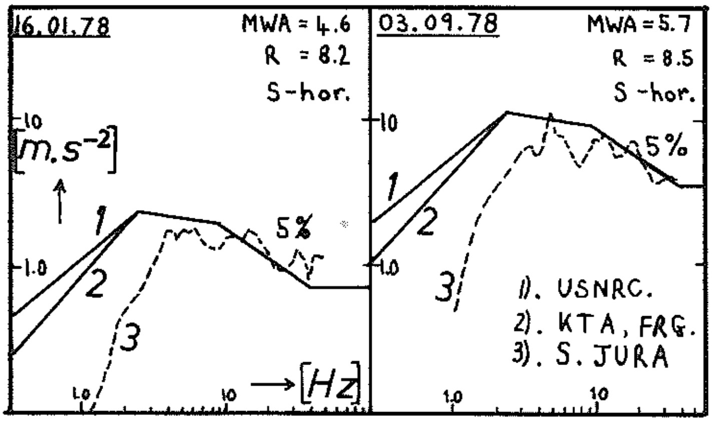

Fig. 1 Comparison of single degree of freedom response spectra (Swabian Jura, FRG) with standard response spectra scaled to peak horizontal acceleration.

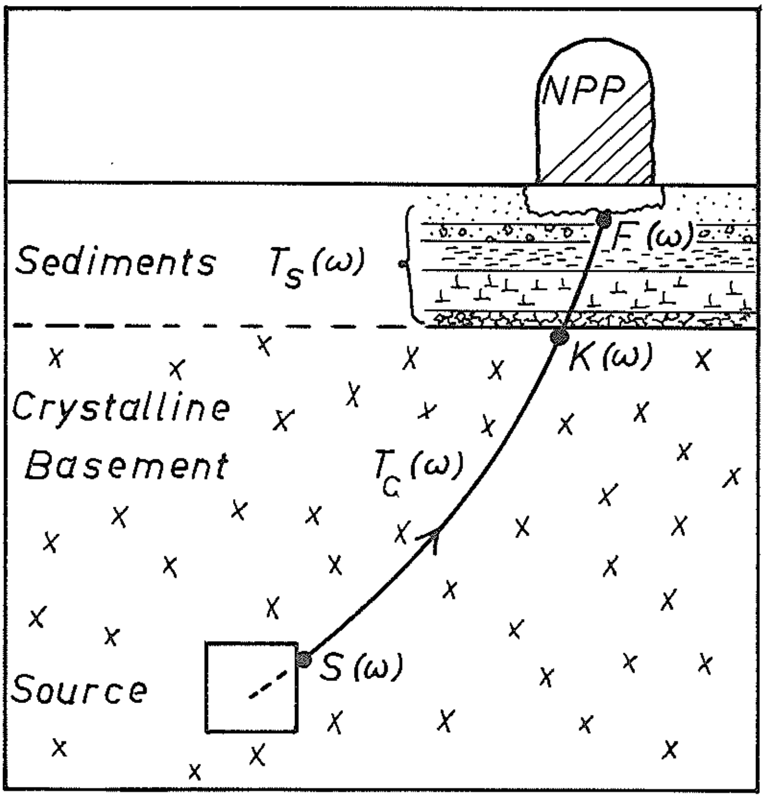

Fig. 2 The physical model. Depth horizons for the synthetic Fourier spectra are indicated.

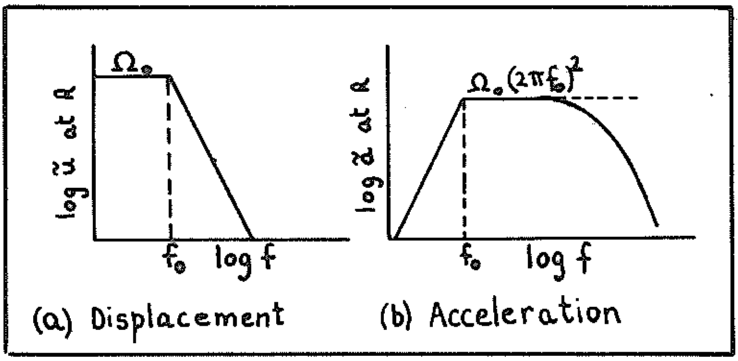

Fig. 3 Fourier amplitude spectrum of (a) displacement and (b) acceleration at distance R.

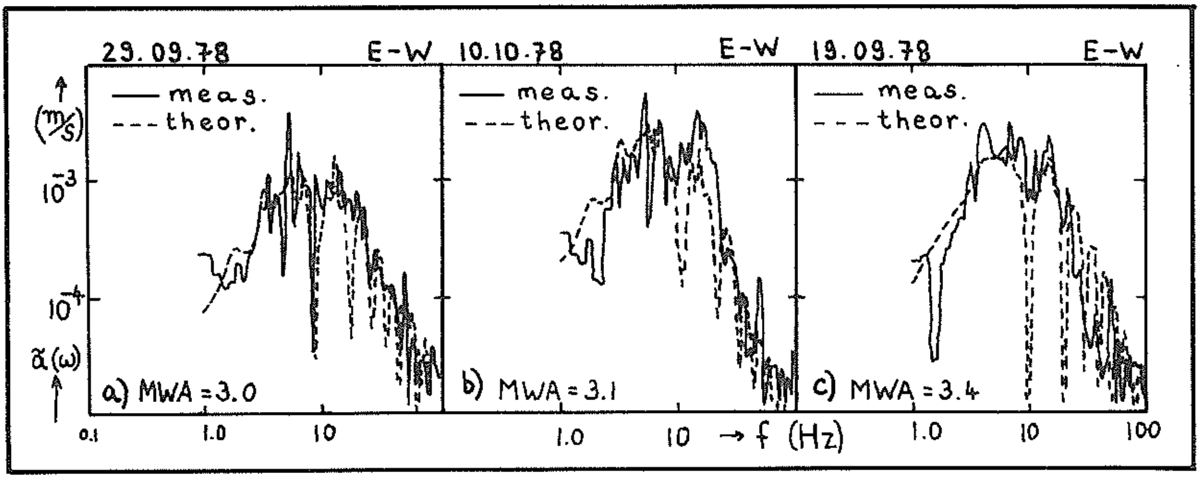

Fig. 4 Real and synthetic Fourier amplitude spectra of acceleration (redrawn from Scherbaum /12/), for Swabian Jura aftershocks.