Earthquake Design Response Spectra for Nuclear Installations in Switzerland

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ABSTRACT

A statistical evaluation of strong motion records typical for the seismotectonic conditions existing in Switzerland was made to develop guidelines for establishing and reviewing earthquake design spectra for nuclear installations in Switzerland. Selection criteria, such as focal parameters of the earthquake, distance from epicenter to recording station, local conditions at recording station, and quality of the strong motion data were determined to select a final data set of 19 records on rock and 22 records on stiff alluvium out of more than 200 records predominantly from Southern Europe. A statistical analysis of these data was made to determine the 84 percentile piecewise linear design response spectra. The comparison with the horizontal US NRC spectra showed a considerable reduction in response for frequencies lower than 3.5 Hz for rock sites and 2.5 Hz for soil sites. The vertical design spectra could be established as 2/3 of the corresponding horizontal spectra over the entire frequency range.

1. INTRODUCTION

The two most important engineering parameters to be considered in the seismic design of nuclear installations are the peak ground acceleration and the response spectrum. The design peak ground acceleration for sites in Switzerland is determined on the basis of the Swiss seismic hazard maps (Ref. 1). However, no Swiss guidelines exist to establish the design response spectrum. Hence, past design and regulatory practice normally had to rely on the US NRC Regulatory Guide 1.60 design spectra (Ref. 2). Applied to sites in Switzerland, a country with only a moderate seismic activity, it was recognized that the NRC spectra at times introduced an undue conservatism because these spectra cover a broad range of possible earthquake motions. On the other hand, proposed deviations from the NRC spectra by the designer, based on site specific conditions, often could not be supported by the necessary data. Therefore, a study was proposed to develop Swiss guidelines for establishing and reviewing design spectra by means of a statistical evaluation of strong motion records mostly from European countries and typical for the seismotectonic conditions existing in Switzerland.

2. SELECTION CRITERIA FOR STRONG MOTION RECORDS

The selection criteria for strong motion records used in this study were based on the seismotectonic environment in Switzerland. This environment is mainly a result of the tectonic activity along the boundary of the Eurasian and the African lithospheric plates (Fig. 1). For example, the Adriatic promontory as part of the African plate reaches deep into the Eurasian plate and is responsible for the earthquake activities along its boundary in Italy, Southern France, along the Alpine arc, and along the Yugoslavian coast of the Adriatic sea.

As a consequence of the general plate movements (see large arrows in Fig. 1), a compressional stress field along the Alpine arc with its major stress perpendicular to the arc (see small black arrows in Fig. 1) is generated. Switzerland is situated just to the north of this plate boundary and consequently the seismotectonic features in this country are largely a result of this compressional stress field.

The evaluation of the focal mechanisms of more than 20 recent earthquakes which occurred in or near Switzerland (Fig. 2) very well supports the uniform stress state in the Alpine region. The focal mechanisms are predominantly of a strike-slip nature with a few thrust faults. The orientation of the maximum horizontal compressive stresses also corresponds well with the orientation of the maximum crustal shortening (dashed lines in Figure 2) derived from kinematic analyses of the neotectonic structural features in Switzerland (Ref. 3).

Based on the described seismotectonic environment of the Alpine region, the main sources of suitable strong motion records were identified as Northern Italy, Western Yugoslavia, Northern Greece and Southern Germany. Due to a substantial increase of the data base in these countries in the last decade - no strong motion events have been recorded in Switzerland so far - it was possible to collect a comprehensive data set. It consists of more than 200 records from earthquakes which occurred in these countries in the last 15 years. Furthermore, a number of records from Argentina and the USA, which were also considered applicable from a seismotectonic point of view, were included in the data set.

In addition to the general seismotectonic criterion, a number of specific selection criteria which were applied to the earthquake events were defined as shown in Table I. An important criterion concerns the earthquake magnitude. Due to the limited seismic hazard in Central Europe, only earthquakes with Richter magnitudes lower than about M_R = 6.5 were considered relevant for the study. The other criteria relate to further earthquake parameters such as focal depth, attenuation, etc.

In a subsequent step, the strong motion records of the selected events were subjected to further selection criteria shown in Table II. These criteria guarantee a high quality of the selected data set, and consider the site conditions as well as some limits with respect to the strong motion characteristics of the records.

The application of these selection criteria to the total data set resulted in a reduction of the number of records to 46 records on rock and 52 records on stiff alluvium.

Most of the collected records were only available in uncorrected form. Because the use of such data usually leads to unreliable response spectra, especially in the velocity- and displacement-controlled frequency range, they had to be corrected (instrument and baseline correction). All records were corrected using the Basili and Brady method (Ref. 4). The filter parameters were chosen based on the total duration and the duration of the strong motion phase of each record.

3. SELECTION OF FINAL DATA SET AND STATISTICAL EVALUATION OF RESPONSE SPECTRA

The selection of the final data set was guided by statistical considerations. The aim was to develop a data set, which could best represent the seismic hazard situation at the Swiss nuclear power plant sites which are located in the Swiss Molasse basin and the sedimentary formations to the north of this basin. Because the seismic hazard is characterized mainly by the earthquake size and the distance to the relevant seismic sources, appropriate distributions of the earthquake magnitudes and the distances between epicenters and recording stations were postulated for the safe shutdown earthquake level (SSE) in this region. Figure 3 shows the distributions represented by the final data set of 19 records on rock and of 22 records on stiff alluvium. Each of these records consists of two horizontal components and a vertical component (acceleration time histories).

The spectra evaluation procedure used in this study is mainly based on the Newmark and Hall method (Ref. 5). It consists of two major steps. In the first step, the ground motion parameters are determined as follows:

- Evaluation of maximum accelerations A, velocities V and displacements D of each component of the selected records.
- Calculation of the mean values $\overline{A}$, $\overline{V}$ and $\overline{D}$ of these maxima and of the relationships $\overline{V/A}$ and $\overline{AD/V^2}$, with subsequent scaling of the $\overline{V}$ and $\overline{D}$ values to $\overline{A} = 1.0$ g.

As a result of this analysis step, the scaled velocities are about 60-64 cm/sec for the horizontal and 54-57 cm/sec for the vertical direction (higher values for rock, lower ones for alluvium). The scaled displacements were found to be in the range of 8-10 cm. Concerning the ratio of vertical to horizontal ground accelerations, mean values of 0.65 for rock and 0.53 for alluvium were obtained. The corresponding design ground motion values are summarized in Table III.

In the second step, the spectral amplification factors are evaluated. This procedure consists of:

- Evaluation of the response spectra for the damping values of 0.5%, 2%, 5% and 10%, and computation of the amplification factors for the accelerations (A_a), velocities (A_v) and displacements (A_d) for each component of the selected records.
- Statistical analysis of the amplification factors for each group of records (rock horizontal, rock vertical, alluvium horizontal, alluvium vertical) at 80 frequency points. Typical results of this statistical evaluation are shown in Figure 4 (mean plus one standard deviation $m+\sigma$, rock horizontal).

- Subdivision of the frequencies, for which amplification factors were computed, into ranges according to the Newmark method as indicated in Figure 4: $f_2 \div f_3$ = acceleration controlled, $f_1 \div f_2$ = velocity controlled, $f < f_1$ = displacement controlled.
- Averaging of the $m+\sigma$ amplification factors within each frequency range and construction of the piecewise linear design response spectra, by scaling to mean ground motion values $\overline{A}$, $\overline{V}$ and $\overline{D}$, respectively.

The advantage of this procedure lies in the independent treatment of the three frequency ranges (acceleration, velocity and displacement controlled ranges). Thus, the resulting spectral shapes are not dominated by one of the ground motion parameters, e.g. the maximum ground acceleration.

4. RESULTS AND CONCLUSIONS

The final results of this study, the smoothed design response spectra for nuclear installations in Switzerland are shown in Figures 5 and 6 for rock and alluvium sites, respectively (horizontal motion). The 84 percentile amplification factors determined statistically for each frequency range were used without modification.

The information which is needed to construct the design response spectra (ground motion and amplification factors) is summarized in Table III for horizontal excitation. The statistically determined vertical spectra showed a reasonably good agreement with the horizontal spectra scaled to 2/3 g. Thus, to allow an easy application in engineering practice, the vertical design spectra were established as 2/3 of the horizontal ones over the entire frequency range. In addition to the values of Table III, two frequencies had to be selected to define the design spectra in the range between rigid body motion and maximum acceleration response. These frequencies were chosen as 33 Hz and 10 Hz, respectively.

Figure 7 shows the comparison of the resulting horizontal design response spectrum on rock for the damping value 2% with corresponding results of other studies. For frequencies higher than about 10 Hz, the US NRC (Ref. 2) and the Mohraz (Ref. 6) spectra are slightly lower than the spectrum proposed in this study. In contrary, the English spectrum (Ref. 7) is about 20% higher, which is a result of the large portion of smaller magnitudes and shorter epicentral distances of the earthquakes considered in that study. In the frequency range of maximum accelerations (5-10 Hz), the spectra in Figure 7 show very good agreement. Larger differences are observed in the range of frequencies lower than about 5 Hz. Similar conclusions as described for rock can be drawn when comparing the spectra for alluvium.

Compared with the widely used US NRC spectra, the spectra evaluated in this study represent a considerable reduction in response for frequencies lower than 3.5 Hz at rock sites and 2.5 Hz at alluvium sites. This fact is due to the exclusion of very large earthquakes and soft soils in this study.

The proposed design response spectra can be used in the seismic design of nuclear installations and other high-risk structures founded at or near the ground surface. They are applicable in many parts of Switzerland and in regions adjacent to Switzerland where seismotectonic conditions prevail which are similar to those established in this study. Exceptions should be considered in areas of higher seismicity or in areas with seismically active faults as well as at sites with rather soft soil conditions.

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Table I: Summary of the selection criteria for earthquake events

Parameter	Selection criteria
Principal stress directions	Compressional stress regime with uniform stress orientation
Focal mechanisms	Strike-slip or thrust fault mechanism or combination of both
Upper limit of earthquake magnitude	Magnitude M > 7.0: excluded M = 6.5 to 7.0 on a case-by-case basis M < 6.5: accepted
Lower limit of earthquake magnitude	Magnitude M < 4.0: excluded M = 4.0 to 4.5: on a case-by-case basis M > 4.5: accepted
Focal depth	Restricted to maximum 30 km
Attenuation characteristics	Low to medium attenuation characteristics with no major azimuth dependency
Stress drop	Used only as guidance

Table II: Summary of the selection criteria for strong motion records

Parameter		Selection criteria
Quality requirements	Reliability	Only records from suitable and correctly functioning instruments
	Completeness	All three components of the record should be available
	Digitization and correction	Record should be digitized and corrected (instrument und baseline correction)
Strong motion characteristics	Maximum acceleration	In general not smaller than 5% g (no upper limit)
	Epicentral distance	Restricted to maximum 150 km and to minimum 5 to 10 km, (depending on focal depth)
Requirements on site characteristics	Free field behaviour	Record should represent free field conditions
	Soil conditions	Soil conditions should be rock or stiff alluvium

Table III: Design ground motion and design amplification factors

	Rock					Alluvium				
	Maximum ground motion	Amplification factors				Maximum ground motion	Amplification factors			
		0.5%	2%	5%	10%		0.5%	2%	5%	10%
Acceleration horizontal	(scaling factor) 1.0 g	5.61	3.98	2.92	2.21	(scaling factor) 1.0 g	5.61	3.98	2.92	2.21
Velocity horizontal	61 cm/s	4.02	3.16	2.38	1.80	54 cm/s	4.85	3.73	2.79	2.08
Displacement horizontal	15 cm	4.80	3.90	3.20	2.50	15 cm	6.00	4.70	3.50	2.70
Vertical spectra = 2/3 of horizontal spectra over the entire frequency range										

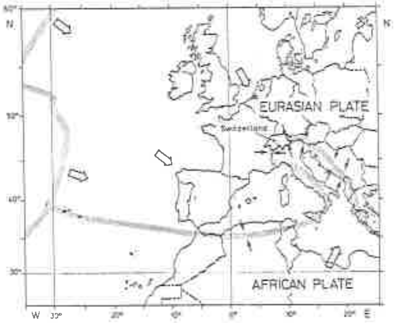

Figure 1: Location of plate boundary between the Eurasian and African lithospheric plates in the Atlantic ocean and in the western Mediterranean region

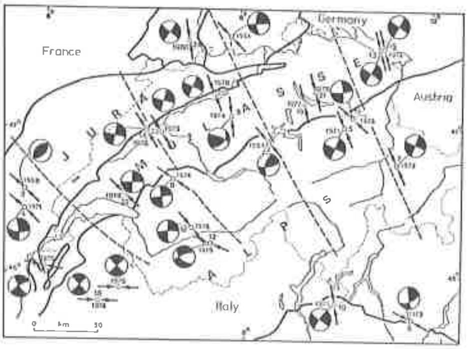

Figure 2: Fault-plane solutions of recent earthquakes in Switzerland (Ref. 3)

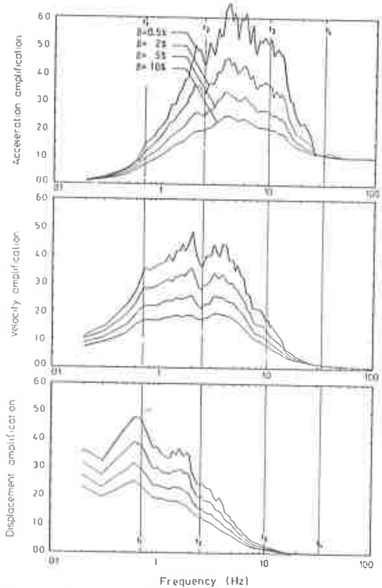

Figure 4: 84 percentile amplification factors of the evaluated horizontal rock records (β = damping)

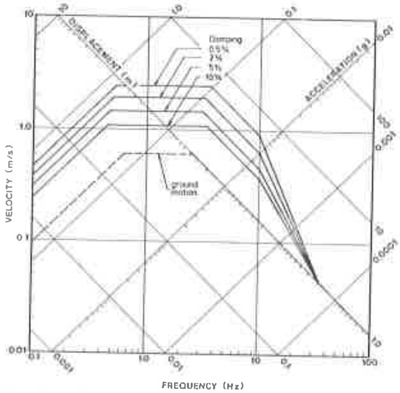

Figure 6: Horizontal design response spectra on alluvium

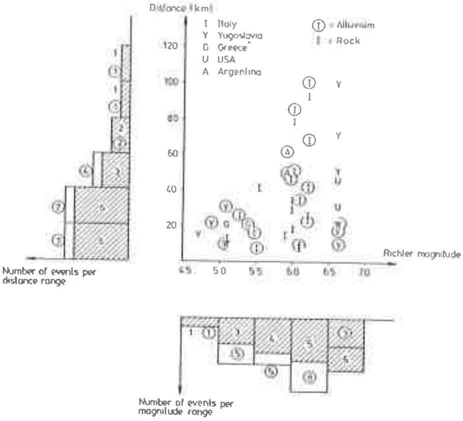

Figure 3: Final data set, distribution of magnitudes and epicentral distances for rock and alluvium sites, respectively

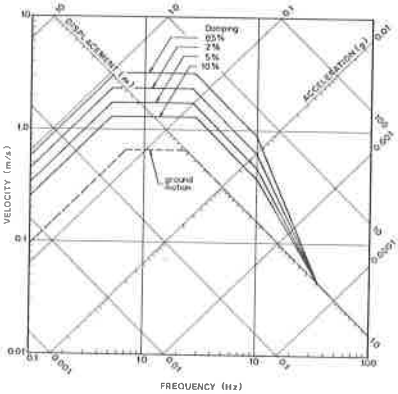

Figure 5: Horizontal design response spectra on rock

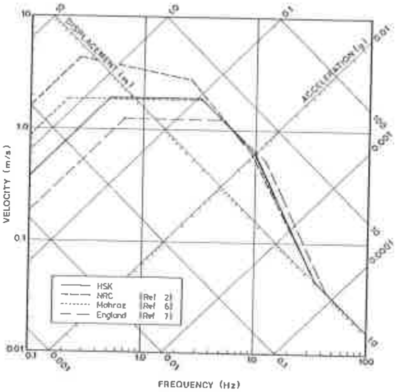

Figure 7: Comparison of the horizontal design response spectrum on rock for 2% damping with the results of other studies