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# EVALUATION OF EARTHQUAKE SAFETY OF NEW AND EXISTING DAMS. TRENDS AND EXPERIENCE

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## SUMMARY

Existing dams have been evaluated according to the current knowledge at the time of their construction. But these evaluations do not satisfy the current safety needs. In practice, for new dams the procedures recommended by ICOLD are applied. The general procedure is clear and straightforward. But often detailed procedures and criteria are needed. Practice has shown that the assessment of the earthquake loading function leads to extensive discussions with the designers. Experiences with deterministic and probabilistic methods are discussed in respect to data acquisition, evaluation of data and reliability of results.

## INTRODUCTION

Earthquake damage to dams has different causes:

- Damage due to shaking, which affect the dam body, the foundation, equipments and installations
- Damage due to displacements along faults crossing the dam foundation or the reservoir, which may cause direct damage to the barrage or a loss of freeboard
- Earthquake induced soil instabilities, which may cause flood waves or a plugging of dewatering conduits

In this paper, we will  concentrate on the assessment of ground shaking parameters needed for the further verification of the earthquake safety of dams.

The earthquake safety of a structure is determined by the earthquake hazard at the site and by the vulnerability of the structure. Dams are relatively simple and robust structures with clear vibration properties. Their vulnerability is therefore much lower than the vulnerability of other structures like buildings. However, because of the high risk associated with a possible failure of a dam, accurate investigations of the earthquake safety of such structures are indispensable, even in regions with low seismicity. Due to the progress made in hazard assessment, hazard assessment for the verification of existing dams will need the same methodologies as for new dams. A good overview on the state of practice in hazard assessment is given in Abrahamson [1].

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Whereas for buildings the safety verifications are specified to a large extent in national and international building codes, for dams an individual procedure has to be followed. Some guidelines are given by the "International Commission on Large Dams" (ICOLD) (References [2], [3], [4]) as well as by national decrees. Especially the loading assumptions are mostly not explicitly given in the existing guidelines, but have to be assessed individually. To perform the hazard assessment, established computer programs exist. The application of such programs is mostly simple, but the reliability of the obtained results is strongly dependent on the underlying model and assumptions. A multidisciplinary experience is therefore required to get reliable results. The amount of preliminary investigations needed is mostly underestimated in practice.

## HAZARD ASSESSMENT

### Loading Assumptions, General Procedure

Verifications of earthquake safety are based on loading functions. These do not correspond to a real earthquake, but are functions adopted for specific earthquake verifications. Some elements of these functions may differ substantially from real earthquakes, such as a longer duration or a broader frequency content. With the use of these functions, uncertainties in the available data shall be covered.

The ICOLD recommendations define a safety earthquake as the Maximum Credible Earthquake (MCE). If such an earthquake occurs, the dam may be damaged, but an uncontrolled outflow of water must be avoided. The serviceability of the dam after the MCE is no more guaranteed. In different countries, following the guidelines for the earthquake safety of nuclear power plants, an Operating Basic Earthquake (OBE) is defined. If such an earthquake occurs, the serviceability of the dam still has to be guaranteed, which excludes larger damage. This loading case is only of interest to the owner of the dam. Some countries, particularly those exhibiting a high seismicity, also define a Design Earthquake (DE), which lies between an MCE and an OBE. The allowed damage corresponds to the MCE, such that a higher risk of exceedance is accepted.

The above loading assumptions correspond to different earthquake recurrence periods (see Table 1). The safety verifications have not only to include the dam body itself, but also safety related elements (like gates, spillways etc.), as well as the discussion of the stability of the valley flanks.

**Table 1: Loading assumptions and allowable damage**

| Loading Assumption | Recurrence Period | Allowable Damage |
|---|---|---|
| Safety Earthquake (MCE) | 10'000 years in most countries | No uncontrolled outflow, major damage is allowable. |
| Design Earthquake (DE) | 3'000 to 10'000 years | No uncontrolled outflow, major damage is allowable. |
| Operating Basic Earthquake (OBE) | 125 to 475 years | Serviceability of the dam has to be guaranteed, only minor damage allowable. |

Taking into consideration the difference in the seismicity of different regions, the loading functions are not generally valid, but must be derived by means of a site specific study. The starting basis is usually the historic seismicity of the region. Till 1910 this seismicity mostly has only been observed, whereas afterwards the seismicity has also been measured. Depending on the specific region, observations from

100 to 2000 years are possible. Older earthquakes show a great uncertainty in respect to date, location of epicenter and intensity.

In Figure 1, the main steps of a probabilistic seismic hazard assessment is shown. The gray shaded steps correspond to basic data needed and are also valid for the deterministic assessment.

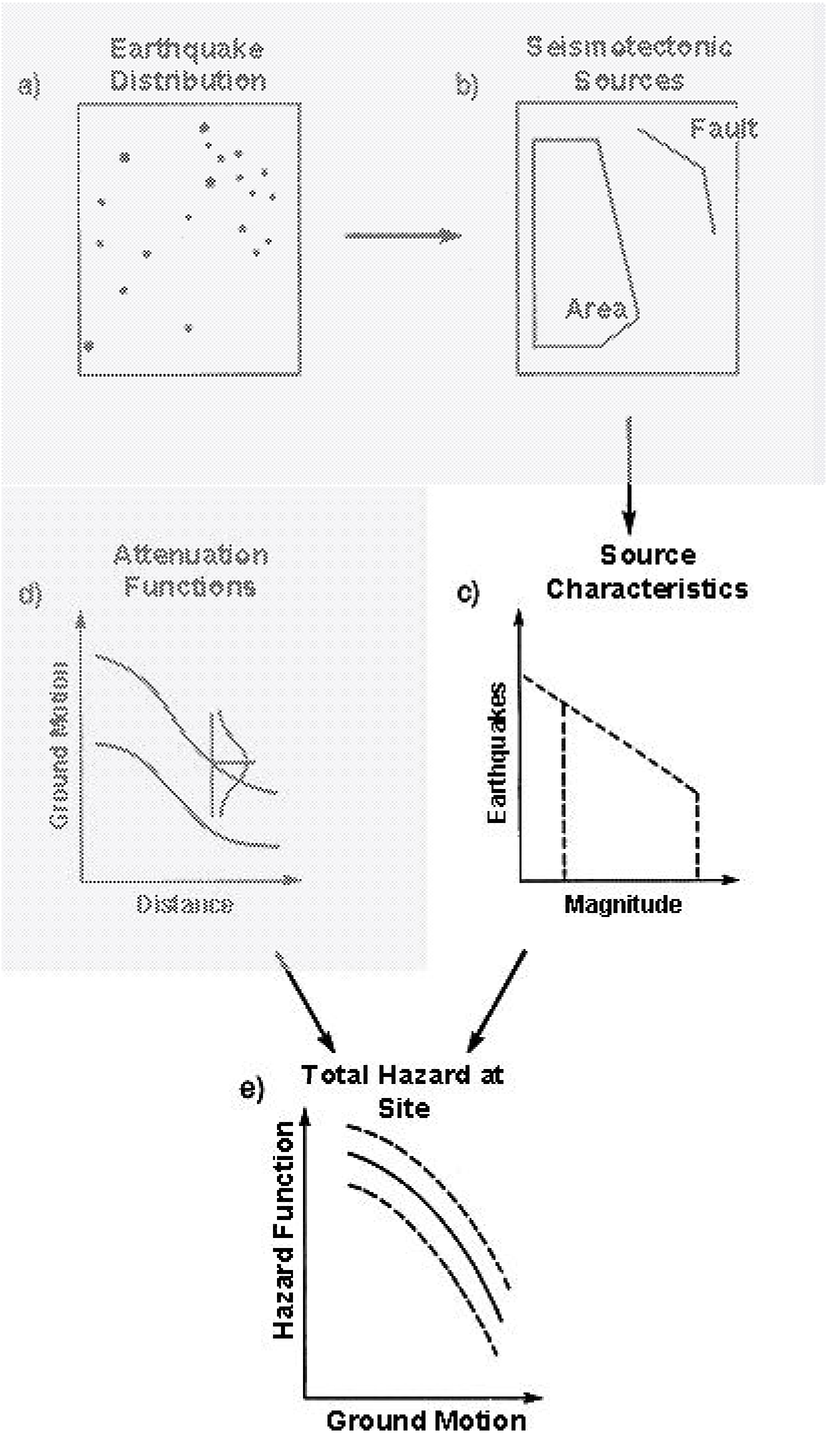

**Figure 1: Main steps of a probabilistic seismic hazard assessment**

Earthquake catalogues nowadays are mostly free accessible (CD-Roms or Internet, e.g. [5]). For a specific region, different catalogues can be found, each with different data structure, completeness and reliability. Obviously the reliability of the derived loading functions strongly depends on the completeness and reliability of this basic data. In practice, all available catalogues have to be evaluated, homogenized (in respect to magnitude etc.) and adjusted for double entries. Worldwide, the earthquake catalogues of different countries are in progress of being updated and revised by national institutes. When performing a site-specific study, it is worth contacting these institutes for updated data.

In Figure 2, a typical illustration of a revised catalogue is shown, within a radius of 200km around a dam in North-East of Turkey. For this example, over 30 catalogues with different size and data reliability have been used and homogenized.

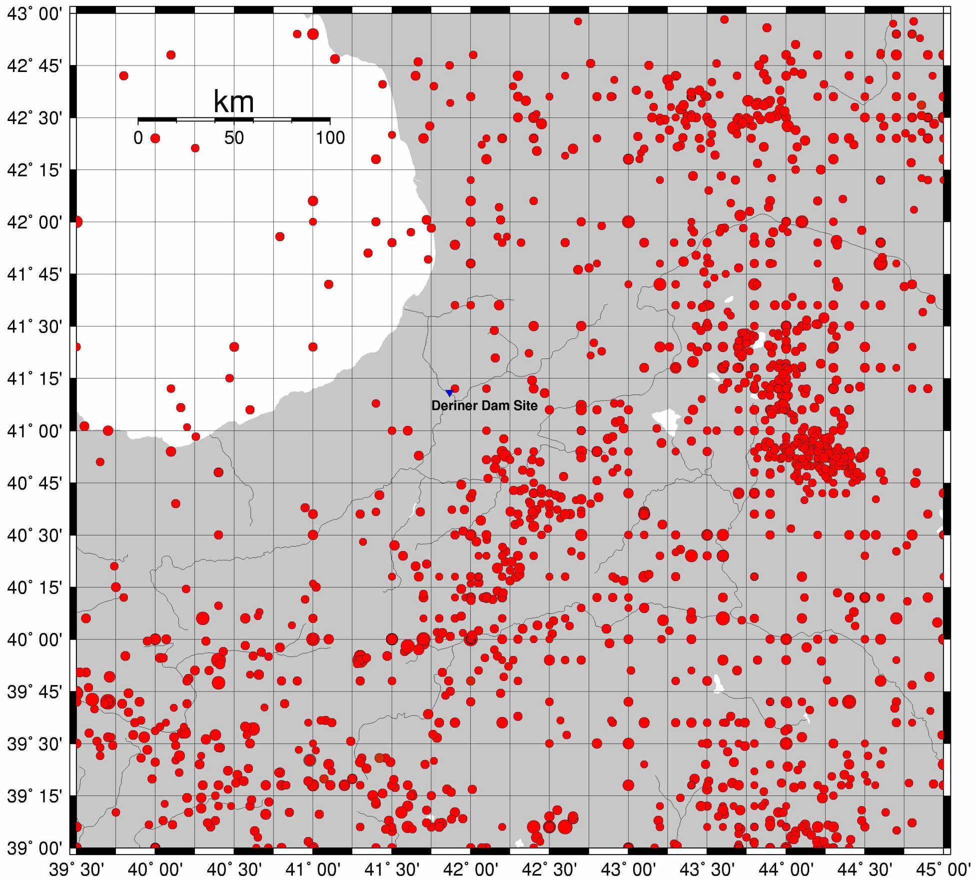

**Figure 2: Observed and measured earthquakes, within a radius of 200km with magnitudes $M_w$>4 to 8, for the period 1'000 b.C. to 1999 a.D.**

In general, even in countries with high seismicity, only faults along which major earthquakes have occurred in the past are already documented. The published data are in general not sufficient to define the seismotectonic pattern around the dam site. The neotectonic pattern can be assessed by means of topographic maps with a scale of preferably 1:50,000, investigating dislocations of river courses, valleys etc. This requires an experienced expert. Unfortunately, in several countries topographic maps are still classified by the military and are therefore not easily accessible. In Figure 3, the seismotectonic conditions derived by the study of the neotectonic pattern based on topographic maps within a radius of 50km from the example dam site are shown.

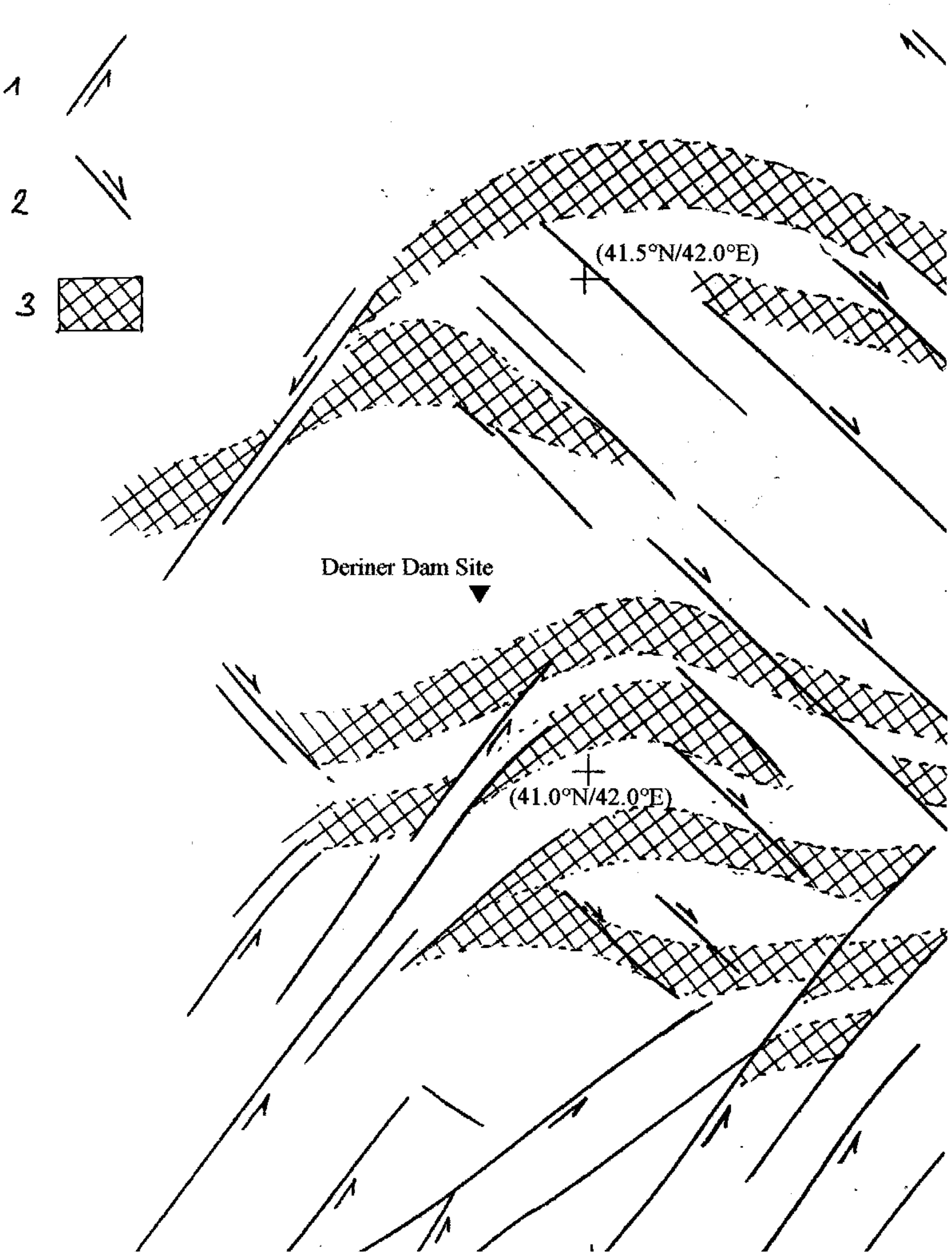

**Figure 3: Pattern of neotectonic deformation in the area within 50 km radius to the site**
(Legend: 1 - sinistral strike-slip fault; 2 - dextral strike-slip fault; 3 - compressional zone, fold, thrust, reverse fault) (Studer [6])

Based on the revised catalogue and the tectonic conditions, a seismotectonic model (seismic sources, linear or area sources) has to be developed. From experience, it is recommended to define the seismic source zones primarily by the seismicity pattern and secondly by the seismotectonic conditions. The inclusion of the tectonic conditions is often not that simple as it may seem at first. In most countries, active faults along which earthquakes have occurred in the past centuries are mapped. But the seismicity data and the neotectonic deformations very often do not fit together well. This may have several reasons. First, in areas with thrust faults (as for example the Alps) the observable faults at the surface do often not reflect the situation at larger depths. Secondly, the observed earthquakes, particularly the historical ones, can not always be confidently allocated to one particular fault, even in regions with high seismicity.

Figure 4 shows the difficulty to indicate historic earthquakes to individual faults. For this reason the determination of seismic source zones instead to rely only on fault structure is often a reasonable approach.

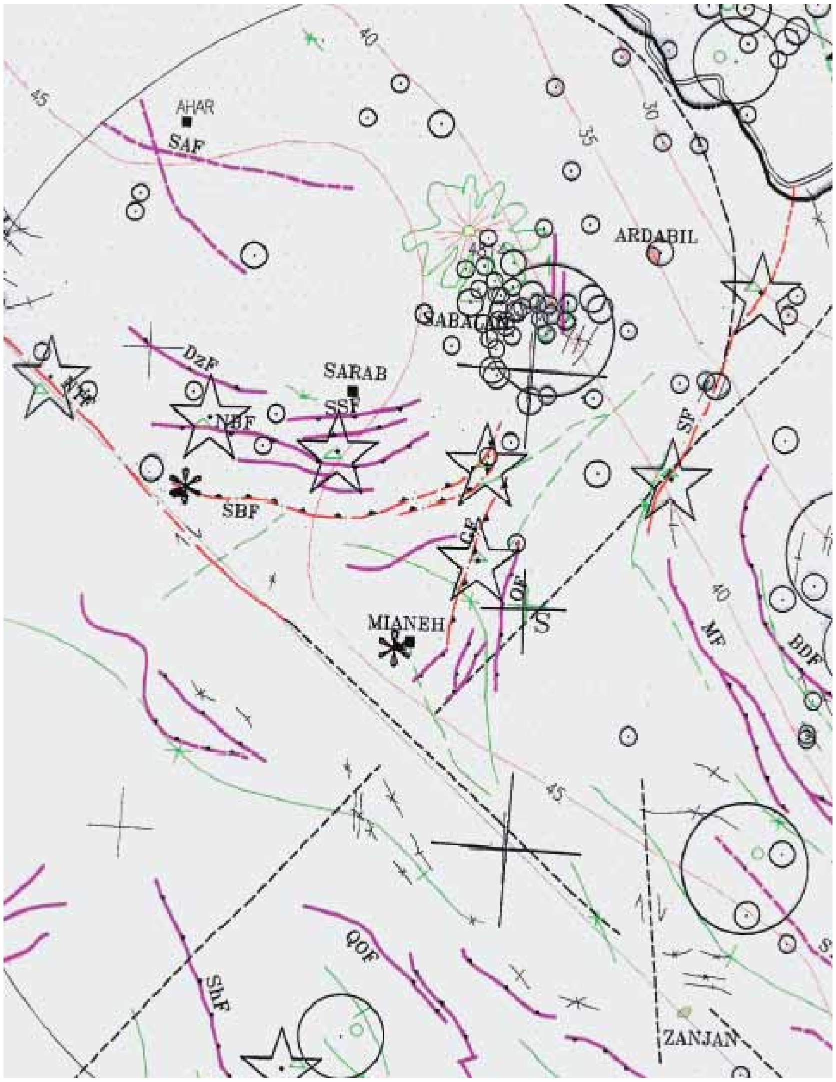

**Figure 4: Known faults and seismicity in North-West Iran [7]**

The seismic source zones are selected in order that their dimensions reflect the uncertainties in locating the observed earthquakes, and that each zone shows a homogeneous seismic activity. It is further important to check the completeness of the catalogue for each seismic source zone, and to change the zone parameters appropriately. Seldom a catalogue is found to be complete for the different zones.

A valuable tool in defining the source zones is a map of the energy release of the past earthquakes (Figure 5).

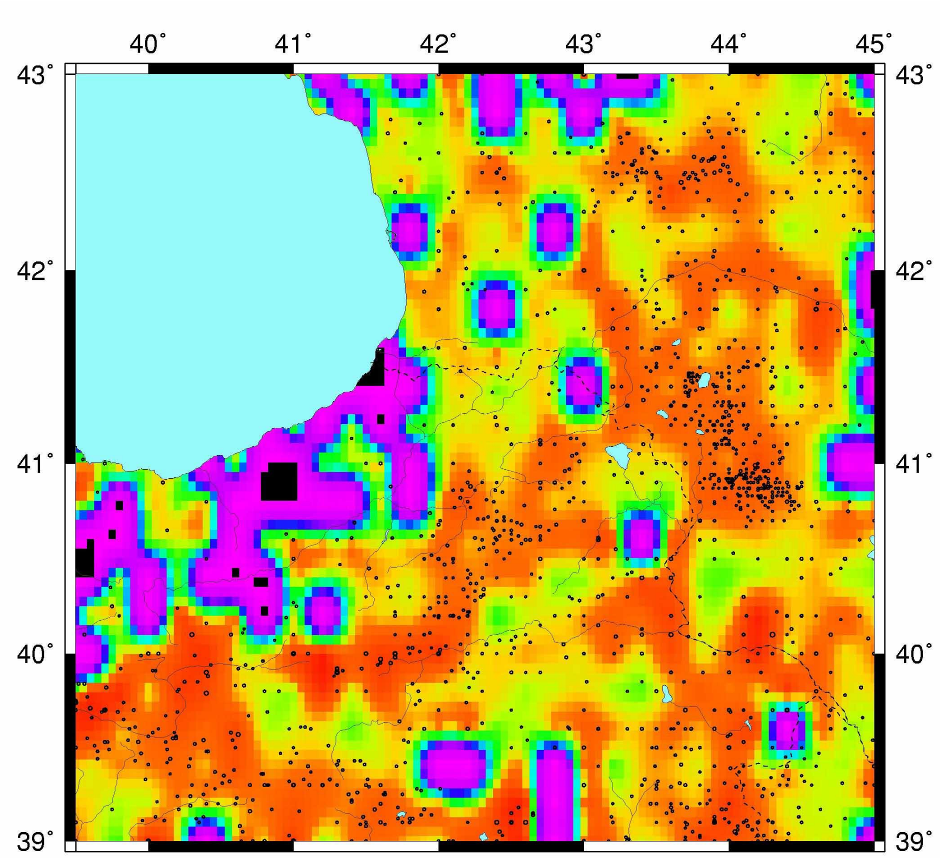

**Figure 5: Energy release corresponding to the earthquake catalogue in Figure 2; colours coded from black/blue (low energy) to red (high energy) (Studer [5])**

Figure 6 shows an example of the seismic source model derived from the seismicity pattern (Figure 2), the pattern of neotectonic deformation (Figure 3) and the energy release (Figure 5). Within a radius of 50km the tectonic characteristics of the site have been considered for the selection of the seismic source zones, whereas for greater distances only the seismicity was considered. It is apparent that the chosen seismic source model will highly influence the results of a hazard calculation.

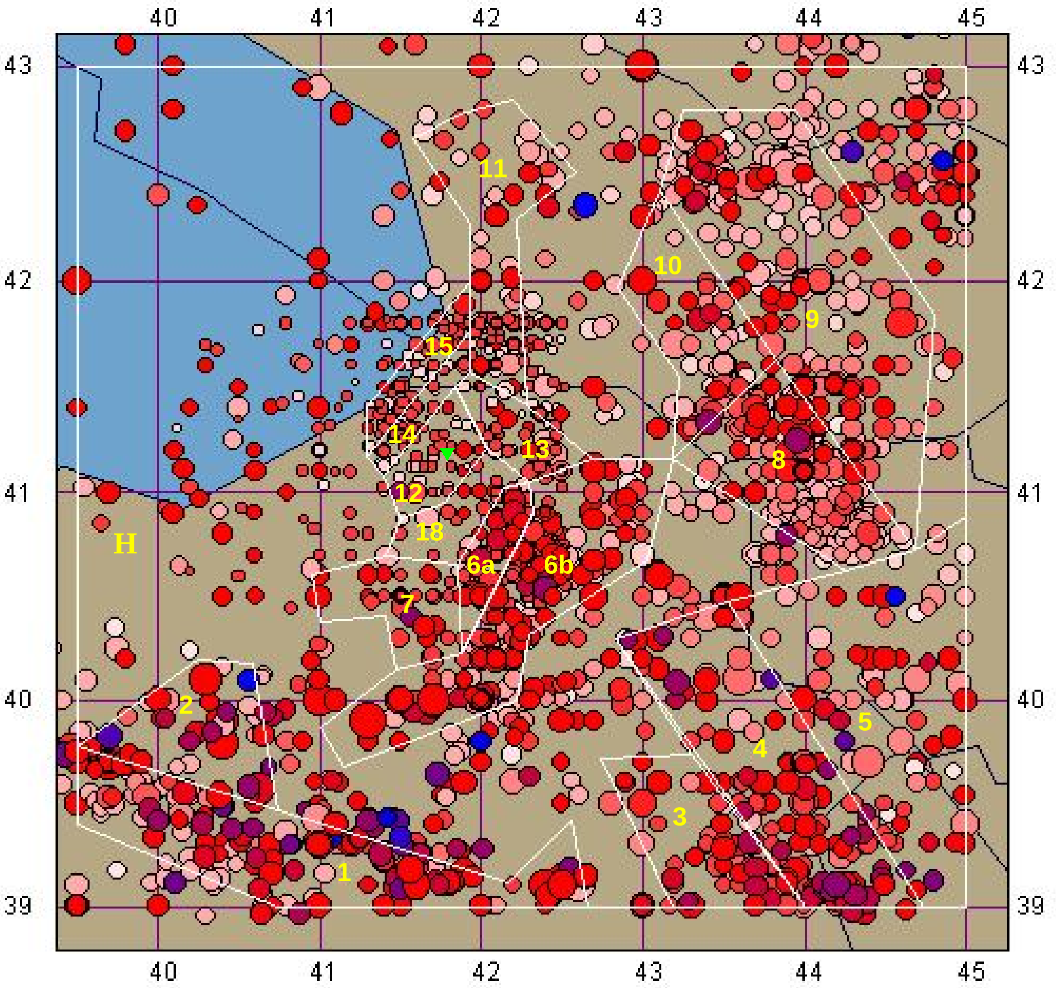

**Figure 6: Seismic source model corresponding to the situation in Figure 2**

It has to be decided how accurate the details of the seismic pattern have to be followed. Each zone is assumed to have homogeneous characteristics. Taking into account the accuracy of the location of historic earthquakes, particularly those before 1900 and the fact, that the smaller the size of the seismic source zones, the smaller is the existing database to define the zone characteristics, the selection of a large number of small zones is not recommended. Instead, a smaller number of larger zones should be selected. The influence of the shape and the size of seismic source zones should be investigated by parametric studies in the hazard calculations.

## Seismic Hazard Assessment at the Site

Two different approaches are possible to assess the seismic hazard at a specific site: the deterministic and the probabilistic approach. These approaches differ in the effort needed as well as in the significance of the obtained results. Table 2 shows some advantages and disadvantages of these methods.

**Table 2: Comparison of deterministic and probabilistic method**

| | **Deterministic Method** | **Probabilistic Method** |
|---|---|---|
| Advantages | - Simple method, low effort needed<br>- Only the greatest events are considered (e.g. greatest historic events with an addition for a longer return period, as for example half a magnitude or derived from tectonic data) | - Statements about recurrence periods are possible |
| Disadvantages | - No statements about recurrence periods are possible<br>- The conservativeness is not known | - The whole earthquake catalogue has to be prepared. |
| Usability | - Usable for MCE<br>- Not usable for DE or OBE, for a specific recurrence period | - Universally usable |

In practice, the deterministic as well as the probabilistic method are used. The probabilistic method is preferred today, particularly in regions where the seismicity is being deeply investigated (such as in USA, Europe, parts of Asia). But one has always to be skeptical about the accuracy of the results. For both approaches, the seismotectonic model is the basis for further analyses. In addition, both methods require extrapolations and further assumptions. For the high recurrence periods as of the MCE, the uncertainties are very high for both approaches.

The principal steps of a probabilistic seismic hazard assessment have been depicted in Figure 1.

For each seismic source zone, corresponding parameters which reflect the seismicity of the zone are needed for the calculation. These parameters are obtained using the Gutenberg-Richter law [8]:

$$\log N(M) = a - bM$$

where M represents the magnitude and N the number of earthquakes occurred with magnitude N. The parameters a and b are determined from the catalogue data and are used as input for the numerical calculation. The observed values of b are near unity. The use of the above law needs a careful investigation of the maximum magnitude $M_{max}$, for which the dataset is truncated. For the selection of $M_{max}$, the historic seismicity as well as the seismic potential of the relevant faults have to be evaluated.

For the subsequent calculation, attenuation laws are needed. These laws should reflect the tectonic situation of the region investigated. Most suitable would be attenuation laws obtained directly from observation in the investigated areas, but the available data is often not sufficient. So one has to rely on published attenuation laws for similar tectonic situations. In the literature, beside attenuation laws for peak ground acceleration, also spectral attenuation laws are available, which makes the determination of the design spectra possible. When using attenuation laws, one has to be very careful due to the different definitions used in the laws (like epicenter distance, distance to fault etc.) as well as in the differences in the definition of the horizontal components (largest component, vector addition, average value etc.).

In practice, different computer programs can be used for the calculation (e.g. [9], [10], [11]). A comparison of the results from these programs, for an identical case, showed that the results obtained are almost identical for mean values (Studer et al. [12]). Nevertheless, one has to be careful when considering uncertainties, since the implementation in the different programs does not fully correspond.

In Figure 7, results of a probabilistic hazard calculation are depicted, for different attenuation laws and a frequency of 100Hz (taken as frequency for peak ground acceleration). As basis for the calculation, the seismic source model in Figure 6 was selected. The influence of the selection of a particular attenuation law is evident. Similar figures can be obtained for other frequencies, provided that suitable attenuation laws are used. The enormous scatter between the results using the different attenuation laws reflects the different data background and the quality of the set. Ideally the final design spectra or peak ground acceleration should be derived using logic trees, where the different sources and their characteristics are taken into account with defined weights. Since this would require a very high effort, often the representative peak ground acceleration or spectra are selected based on engineering judgment, loosing information on uncertainties.

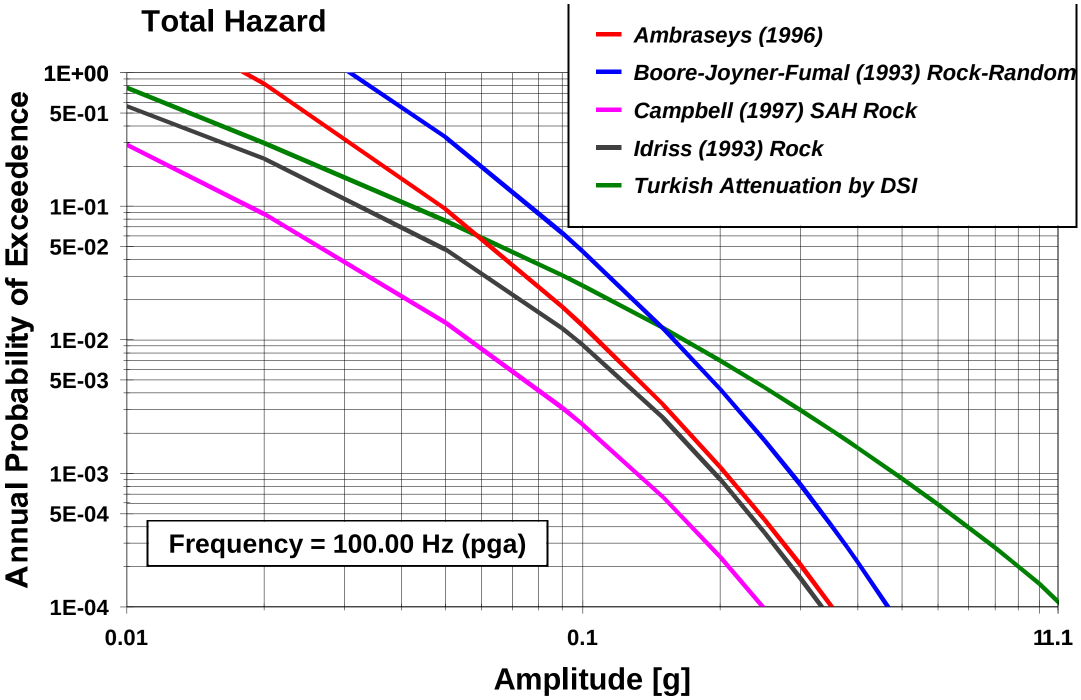

**Figure 7: Results of the probabilistic seismic hazard assessment, for a frequency of 100Hz**

Table 3 shows the results (peak ground acceleration) from probabilistic seismic hazard calculations using an area source model (as in Figure 6) or a line source model. A significant scatter can be seen, even for the same attenuation law. Therefore, the use of a logic tree to define design spectra or peak ground acceleration is strongly recommended.

**Table 3: Comparison of Results for Different Methods**

| Probabilistic Method (return period 10'000 years) | | pga (g) 50% value |
|---|---|---|
| **Line source model** | Campbell&Bozorgnia (2003) | 0.34 |
| | Ambraseys&Douglas (2000) | 0.34 |
| | Joyner&Boore (1997) | 0.32 |
| **Area source model** | Campbell (1997) | 0.35 |
| | Idriss (1993) | 0.40 |
| | Sadigh (1994) | 0.32 |
| | Campbell&Bozorgnia (2003) | 0.47 |
| | Ambraseys&Douglas (2000) | 0.25 |

For safety related structures (dam body etc.) a 84% fractile value should be used, whereas for less important structures 50% fractile values (median values) are sufficient.

The actual loading assumption for the seismic verification is either a design spectrum for elastic calculations, or different time histories for dynamic non-linear calculations. The design spectra are either obtained directly using the spectral attenuation laws, or a standard spectrum is scaled at the peak ground acceleration. The choice of the appropriate procedure is based on engineering judgment.

Where non-linear calculations are necessary, the needed time histories are derived artificially from design spectra or from modified recorded time histories. Boundary conditions for the selection of appropriate time histories are:

- the target design spectrum
- for the deterministic approach: the characteristics of the earthquake events used
- for the probabilistic approach: the results of a deaggregation

Artificial time histories can be obtained using different computer programs and methods (as [13],[14],[15]). Further recommendations can be found in national guidelines.

It is strongly advised against using solely the peak ground acceleration for the seismic verification of dams. Nevertheless this method is still adopted in practice, due to the relative rapid and simple procedure. Instead it is recommended to develop seismic response spectra as discussed, which include much greater information content. To get reliable results, a close cooperation between seismologists, earthquake engineers and geologists is needed.

## METHODOLOGY FOR SEISMIC VERIFICATION

The methodology for the seismic verification is different for existing dams or new projected dams. The methodology for new dams is regulated by the recommendations of ICOLD. For existing dams, the determination of the soil parameters as required for new dams is mostly not possible due to financial reasons. Instead, the behavior of the dam and of the used materials is often known. Needed dynamical material properties can be deduced by correlation with static test results. Generally, only for important structures and critical situations additional material tests are performed. Detailed guidelines have been developed for the verification of the seismic safety of dams (e.g. Working group [16]). A good overview of existing guidelines is given in Reilly [17].

## SEISMIC INSTRUMENTATION

It is the opinion o the author that the seismic instrumentation is a must for important structures in seismic active areas. In practice however, the owners often are not convinced that the seismic instrumentation is a necessity, mostly for financial reasons. However, the cost for a seismic instrumentation is negligible in comparison to the other expenses. In addition, the benefits of a seismic instrumentation would be very high for the owner of the dam, because in case of an earthquake event the behavior of the dam is monitored and costly verifications can be often avoided. A seismic instrumentation furthermore allows the verification of the representativeness of the model chosen by the engineer for calculation, and supports the development of modern and reliable computation methods.

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