13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 1794

SWISS GUIDELINES FOR THE EARTHQUAKE SAFETY OF DAMS

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SUMMARY

The Dam Section of the Federal Office for Water and Geology has commissioned the preparation of guidelines on the assessment of the earthquake behavior of dams. They shall ensure that the earthquake assessment of the Swiss dams be performed according to state-of-engineering practice. The main goals are the protection of population downstream against loss of life and injuries and against property damages as well as direct and indirect economic losses. These goals are fulfilled by requiring that, for a specific safety assessment earthquake, no failure with uncontrolled release of reservoir water occurs nor do the dams sustain any damages that could jeopardize their integrity. The guidelines are comprehensive, providing detailed implementation procedures. Simple calculation methods are also included, that can be used to assess the safety of the smaller dams.

INTRODUCTION

The Dam Section of the Federal Office for Water and Geology is the supervising authority for dam safety in Switzerland. In this capacity, it appointed a working group entrusted with the task of preparing guidelines on the assessment of the earthquake behavior of dams. The working group, chaired by the author, consisted of representatives of the Society for Earthquake Engineering and Structural Dynamics, the National Committee on Dams, dam owners and specialized engineers. The Seismological Survey was also consulted.

The primary task of the Working Group was to document the assessment principles and procedures that had been applied in past reviews of earthquake behavior of dams in Switzerland. In the process, it was verified that they still correspond to the present state of engineering, adapting them when needed. It was also necessary to prepare simple assessment procedures for dams of smaller sizes that are judged to pose a non negligible threat to public safety.

The guidelines are formally enforced since January 2004, although they have already been applied earlier. The rather comprehensive supporting document is subdivided in 7 parts whose content and underlying philosophy are outlined in the paper, together with lessons learned from their application.

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GUIDELINES

Part A - Fundamentals

The ultimate objective is to protect people, the environment and property downstream from death, injury and direct as well as indirect economic losses. Central to the implementation is the corresponding underlying philosophy that specifies that the earthquake dam risk remains limited in a similar fashion at all dams.

The risk R is defined as

$$R = P \cdot C \tag{1}$$

where P is the occurrence probability of an earthquake larger than the safety evaluation one and C are the consequences of dam failure. Limiting the risk to a same value at all dams implies that the chosen probability of occurrence of the safety evaluation earthquake (*SEE*) is lower at dams where failure consequences are larger. This led to the specification of dam classes, a new concept in Switzerland in this context. The chosen probability of exceedance of the *SEE* thus depends on the dam class. Also, fewer analysis uncertainties are allowed at dams where failure consequences are large, i.e. the assessment procedures are more stringent in such cases (the minimal assessment procedures are thus also class dependent), as are the required qualifications of the lead engineer or analyst.

Consistent with this philosophy, the compulsory assessment has to be performed for the safety evaluation earthquake *SEE* only, and not for a basis operation earthquake *OBE* (this is left to the owner's choice). For the former, it is required that no uncontrolled release of reservoir water takes place and that safety-relevant appurtenant structures and components (e.g. outlets) remain operational or can be brought back into operation quickly.

Dam classes

3 dam classes are retained, associated with the severity of consequences following a hypothetical uncontrolled release of reservoir water (class 1 for large consequences and class 3 for low consequences). In the absence of any related hard data, the combination of dam height and reservoir volume of Figure 1 is taken as a substitute for class allocation.

Dams that retain water on an exceptional basis (flood-protection dams) are automatically assigned to class 3, irrespective of their height and reservoir volume.

91 dams fall in class 1. These are 79 concrete and 12 embankment dams, among them the 285 m high gravity dam of Grande Dixence and the 250 m high arch dam of Mauvoisin. 78 dams fall in class 2 (39 concrete and 39 embankment dams). While all class 1 and class 2 dams are under direct supervision of the federal state, some of the class 3 dams are under direct supervision of the cantonal states. Their exact number is not known, of the order of a few hundreds. They are mostly embankment dams.

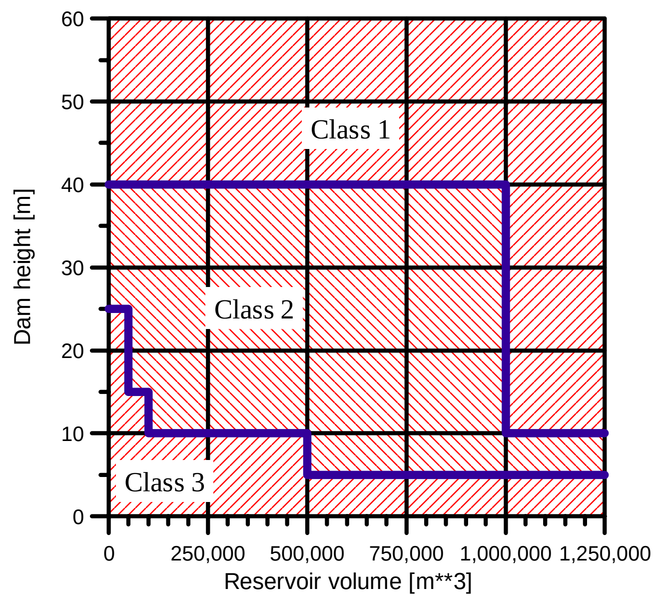

Figure 1 - Dam classes

Qualifications

It has been recognized that the qualifications of the lead engineer or analyst in terms of knowledge and experience are as important as the modeling approach in order to guarantee a sound assessment of the earthquake safety. This led to the following requirements, also a new element of the guidelines:

- For dams of classes 1 and 2: Documented technical education and experience in dam engineering, in dam safety and in earthquake engineering;
- For dams of class 3: Education as a civil engineer with documented experience in hydraulic structures.

Documentation and declaration of conformity

In order to foster clear statements and emphasize the personal responsibility of the lead engineer or analyst, it is required that the assessment contains a declaration of conformity. The lead engineer or analyst, who herewith confirms that the requirements of the guidelines are satisfied in full, must personally sign it. In case not all requirements are fulfilled, to what extent this is not the case and what remedial measures have been taken must be indicated, and the effectiveness of these measures demonstrated.

Remarks

As mentioned earlier, the assessment has to be performed for the *SEE* only. There are no serviceability requirements (i.e. no verification for an *OBE*), although it is in the interest of the owner of targeting one. Based on the same philosophy, damages that do not result in uncontrolled release of water nor to non-restorable functionality of safety-relevant appurtenant structures and components are accepted.

It is further stressed that the objectives and requirements put forward in the guidelines are minimal ones. They can be replaced by ones that are at least equivalent.

Part B – Safety evaluation earthquake

Existing seismological information form the basis of the probability-based definition of the safety evaluation earthquake. It is given by a set of response spectra and effective peak accelerations (rock outcropping) for various probability of exceedance (return periods).

Probability of exceedance

The exceedance probability is given for a reference time span of 100 years. It is expressed through the associated return period of Table 1, differing for each dam class.

Table 1 - Safety evaluation earthquake

Dam class	Reference time span	Probability of exceedance	Return period
1	100 years	1 %	10'000 years
2	100 years	2 %	5'000 years
3	100 years	10 %	1'000 years

Peak acceleration

Intensities are read from maps that are provided in the guidelines. The effective horizontal peak acceleration a_h is then obtained from the following empirical intensity-acceleration (I_{MSK}-a_h) relation

$$\log(a_h) = 0.26 I_{MSK} + 0.19 \qquad ;\mathrm{a_h}\ \text{in cm/s}^2 \tag{2}$$

The vertical peak component a_v is taken as 2/3 of the horizontal component a_h.

Response spectra

The response spectra retained in the guidelines are those of Eurocode 8. They apply both for horizontal and vertical directions.

Time histories

Appropriately-scaled earthquake records or synthetic records are used in time-domain analyses. They must in any case be compatible with the relevant response spectrum.

In accordance with EC8, the strong-motion duration T_s of synthetic records must satisfy

$$T_s[\sec] = 10 + 50\left(\frac{a_h}{g} - 0.1\right) \quad ; \quad \min.10\sec \tag{3}$$

When a time-domain analysis is conducted, at least 3 sets of stochastic independent time histories need to be considered. The strong-motion duration must thereby vary by ± 5 seconds in 2 of them. Each set is composed of 3 components (2 horizontal and 1 vertical, 3-D analysis) resp. 2 components (1 horizontal and 1 vertical, 2-D analysis).

Remarks

After a few analyses had been performed, it was decided to prepare a set of time histories that can be used directly in the safety assessments. Time histories of strong-motion duration varying from 10 to 30 seconds in 2 seconds steps have thus been artificially generated, 3 motions per duration for each of the 3 response spectra (3 different foundation rocks). Statistical independence between the individual motions has been verified. These 99 individual motions have been put on a CD that is distributed upon request.

Various projects are presently underway in Switzerland aimed at obtaining a more modern description of the earthquake hazard in the country. This part of the guidelines will be revised as soon as these new information are available in a consolidated form.

Part C – Embankment dams

Assessment
The analysis procedure pertinent to embankment dams is reported in the flow chart of Figure 2.

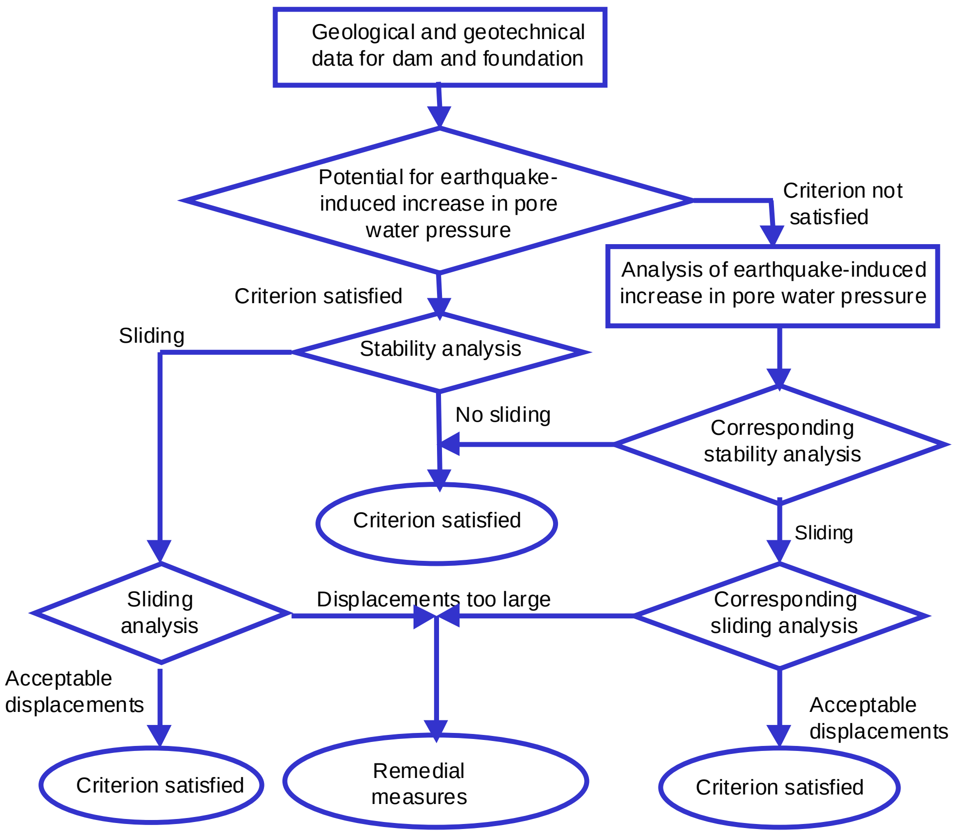

Figure 2 - Analysis procedure for embankment dams

The assessment is based on a two-step analysis. At first, the stability of individual dam parts is systematically evaluated. If the stability is not guaranteed and sliding occurs, then a sliding analysis is performed in a second step. It must then be demonstrated that pre-set displacement limits are satisfied and that the overall dam stability is guaranteed. This implies in particular that a sufficient freeboard remains (no dam overtopping) and that the drainage and core layers continue to fulfill their intended purpose.

Modeling requirements
Modeling requirements depend on the dam class according to Table 2.

Table 2 - Modeling requirements for embankment dams

	Material properties and investigation methods	Modeling and calculation methods
Class 3 embankments	Static properties *New dams:* From tests *Existing dams:* From construction documents or cross comparisons	Simplified stability analysis with equivalent earthquake load, horizontal action alone Simplified calculation of sliding displacements if necessary
Class 2 embankments	Static properties, possibly dynamic properties *New dams:* From tests for static properties and cross comparisons for dynamic properties *Existing dams:* From construction documents for static properties (from tests if none available), from cross comparisons for dynamic properties	Simplified stability analysis based on modal analysis (1 mode, response spectrum), horizontal and vertical excitation Simplified calculation of sliding displacements if necessary
Class 1 embankments	Static and dynamic properties *New dams:* Static and dynamic properties from tests *Existing dams:* Static and dynamic properties from construction documents (from tests if none available)	2D static and dynamic finite-element calculations for dam response Simplified stability analysis based on calculated dam response (horizontal and vertical excitation) Simplified calculation of sliding displacements if necessary

Remark
All the indications necessary to conduct the simplified analyses are included in the guidelines, including formulas, tables and graphs to estimate periods of natural vibration, motion amplification over the dam height and sliding displacements. The procedure recommended for class 3 dams is very straightforward, as exemplified in Figure 3.

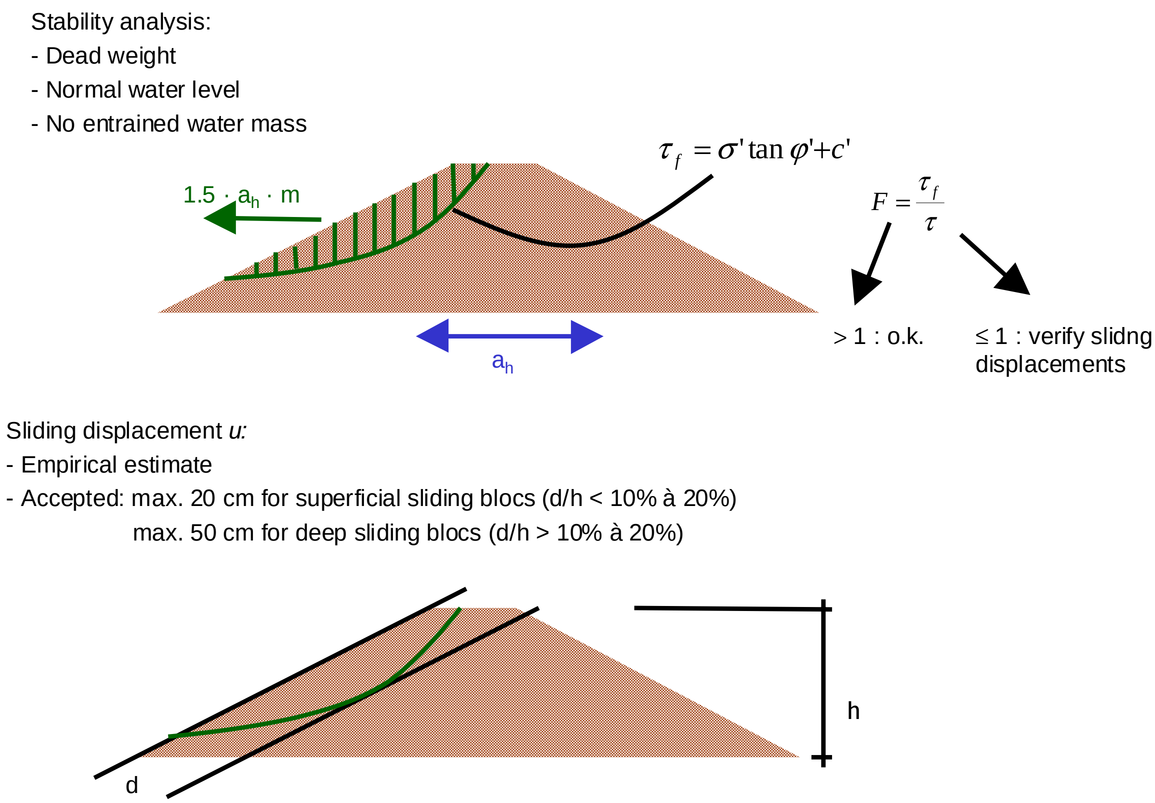

Figure 3 - Calculation procedure for class 3 embankments

Part D – Concrete and masonry dams

Assessment

Both a stress and a stability assessment need to be performed, as well as additional assessments related to appurtenant structures and components, foundation and reservoir banks. The analysis flow-chart is reported in Figure 4.

In the stress analysis, the stresses (or stress resultants) stemming from the combined static (normal operating conditions) and dynamic loads are compared to material strength. In case of overstressing, it must be demonstrated that stress redistribution can take place and that no local instability will occur. Overall aspects such as overturning and sliding are investigated in the stability analysis.

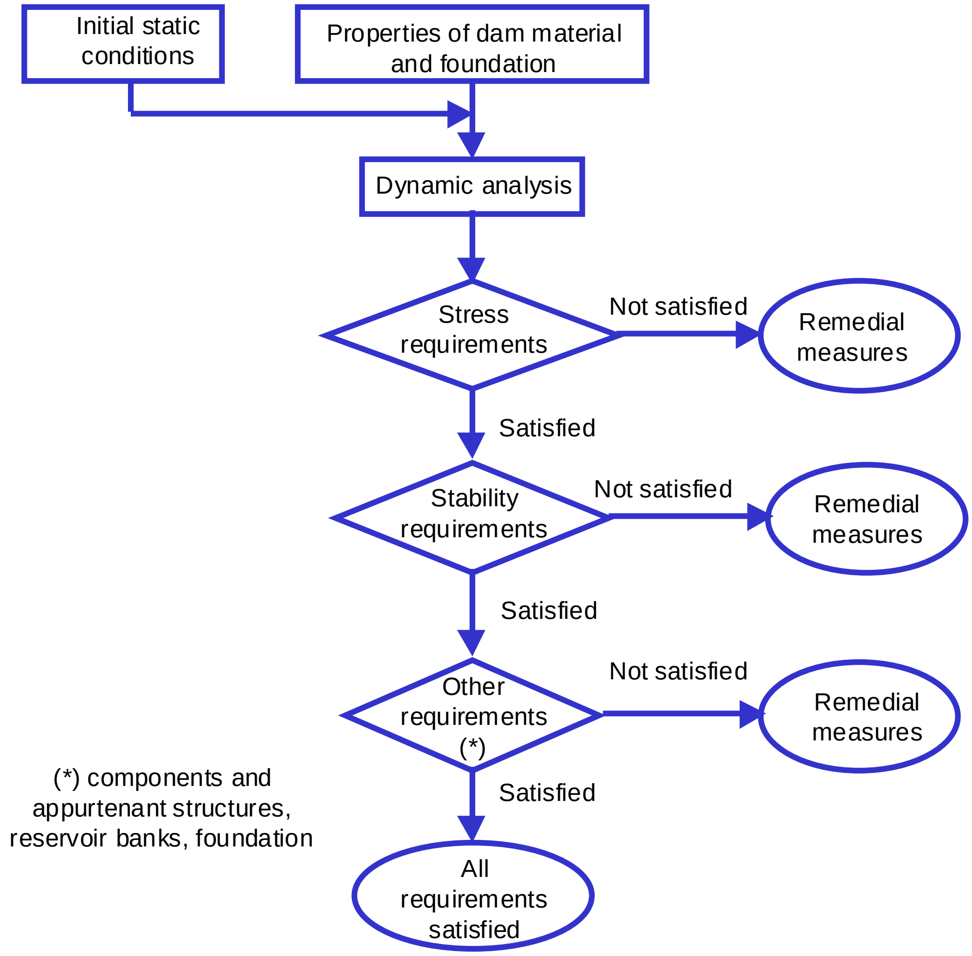

Figure 4 - Analysis procedure for concrete and masonry dams

Modeling requirements
The required modeling details again depend on the dam class, according to Table 3.

Table 3 - Modeling requirements for concrete and masonry dams

Dam class	3	2	1
Dam dynamic characteristics	Empirical	Modeling	Modeling
Modeling	*2D dam:* Beam model or analytical *3D dam:* Arch-cantilever or finite elements *Foundation:* Rigid *Reservoir water:* Entrained mass (incompressible)	*Dam:* Arch-cantilever or finite elements *Foundation:* Springs or finite elements (massless) *Reservoir water:* Entrained mass (incompressible)	*Dam:* Finite elements *Foundation:* Finite elements (massless) *Reservoir water:* Entrained mass (incompressible)

Materials	*Dam:* Linear visco-elastic, characteristics from cross comparisons *Dam-foundation interface:* From cross comparisons *Foundation:* Rigid	*Dam:* Linear visco-elastic, characteristics from dam-specific static tests *Dam-foundation interface:* From cross comparisons *Foundation:* elastic, characteristics from cross comparisons	*Dam:* Linear visco-elastic, characteristics from dam-specific static tests *Dam-foundation interface:* From cross comparisons *Foundation:* elastic, characteristics from cross comparisons
Methods of analysis	Pseudostatic or modal analysis (1 mode, response spectrum)	Modal analysis (several modes, response spectrum)	Time history analysis
Necessary assessments	Stresses Dam stability Foundation integrity Components and appurtenant structures Reservoir sides	Stresses Dam stability Foundation integrity Components and appurtenant structures Reservoir sides	Stresses Dam stability Foundation integrity Components and appurtenant structures Reservoir sides

Remark
Precise indications on the way to perform the simplified analyses are again included in the guidelines. As an example, the ones prepared for the simplified verification of gravity dams is depicted in Figure 5. It involves estimating the fundamental period of vibration, mode shape and pseudo-static forces from a set of curves. The latter were obtained from a series of calculations.

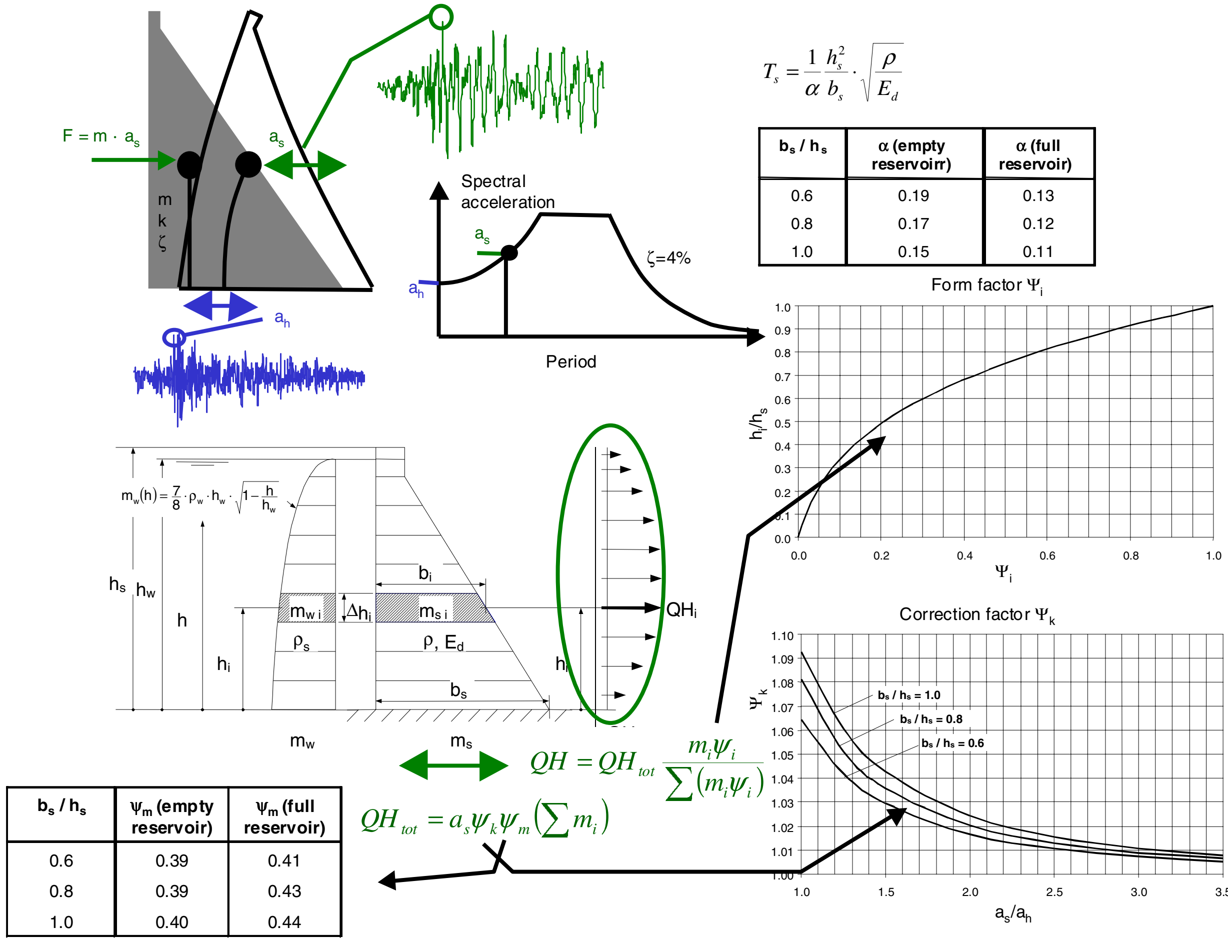

Figure 5 - Calculation procedure for class 3 gravity dams

Part E – River dams

River dams are composed of a structure under water with or without a large one over water (e.g. tall piles supporting a service bridge with heavy machinery). They can further be constructed out of masonry, concrete, reinforced concrete or steel. This variety in structural system and material made it impossible to prepare as detailed recommendations as for the other types of dams. This was also not deemed necessary, as a superstructure has much resemblance (in its functioning and reaction to earthquake action) with a bridge and an underwater structure with a concrete dam; detailed guidelines exist for both these types of structures. This led to the explicit recommendation to use third party guidelines and/or the part of the present ones devoted to concrete dams, respecting in any case the fundamental philosophy of uniform risk and the resulting dam classification (and thus return period and modeling details).

Part F – Strong-motion instrumentation

Strong-motion instrumentation does not only provide important data for research purposes, it also has practical benefits. In particular, a post-earthquake investigation can be decided upon based on the effective site motion rather than on a highly approximate estimate and the behavior of the dam during the earthquake can be reconstructed. The installation of at least 3 strong-motion instruments at all class 1 dams is thus required (1 in the free field, 1 at the crest, 1 at the dam base). Instrumentation of other dams is optional, provided they do not show any abnormal behavior or have any safety defects.

Part G – Post-earthquake controls

Objective and principle
The objective of post-earthquake controls is to identify quickly damages or changes in dam behavior so as to be able to take the necessary steps to protect population and property downstream.

The extent and the urgency of the controls are specified on the basis of the earthquake motion observed or estimated at the dam site. The associated limits are set individually for each dam. For those in which at least 3 strong-motion instruments are installed, the intervention level is set on the basis of the comparison between the accelerations measured at the site and the *SEE* peak acceleration a_h. For those dams that are not instrumented, the levels are set as a function of the estimated earthquake motions at the dam site (estimated site intensity). This is summarized in Table 4.

Table 4 - Intervention levels for post-earthquake controls

Intervention level	Control	Measured a_{max} (in rock / along abutment)	Measured a_{max} (on / in dam)	Estimated MSK intensity
1	Next regular safety check	> 10% a_h	> 20% a_h	IV
2	Within 24 hours	> 25% a_h	> 50% a_h	V – VI
3	Immediately	> 50% a_h	> 100% a_h	≥ VII

Extent of control
The requirements regarding the extent and content of the post-earthquake controls are essentially those specified by the International Commission on Large Dams.

FINAL COMMENTS

The guidelines are largely a formalization of the recent dam engineering practice in Switzerland with regard to the assessment of earthquake safety. Three new main elements have however been introduced:

- The concept of uniform accepted risk with resulting dam classification and, thus, differentiation in probability of exceedance for *SEE* and in modeling detail;
- Compulsory strong-motion instrumentation of class 1 dams; and
- Specification of urgency and detail of post-earthquake controls based on the comparison between site motions and safety assessment earthquake.

Owners and engineers who feared that few dams could fulfill the requirements set forward met the preliminary issue of the guidelines with skepticism. This skepticism was largely put aside after it became clear that this was not the case and that these requirements had *de facto* long been in place. Still, the National Committee on Dams is now creating a working group with the mission of making an independent review of the guidelines.

Several assessments have been performed on the basis of these guidelines, for dams belonging to all classes. The safety requirements were met without taking any remedial measures in all but a few cases. These exceptions were dams whose state and behavior had already been questioned under normal operational conditions or that have a particular structural configuration. In other words, dams that satisfy current construction and safety standards for normal operating conditions were also found to satisfy the requirements related to seismic action. This should actually not come as a surprise. Indeed, the primary structural purpose of a dam is to transfer the large horizontal component of hydrostatic forces into the abutments and foundation. Dams can thus usually also accommodate horizontal earthquake forces that account for many of the destructive damages seen in buildings.

Application examples and download

Formal supervision of the smaller dams, allocated to class 3, has just been introduced. Particular care was thus taken when preparing the requirements for their seismic safety assessments. Application examples have also been prepared. They can be downloaded from the following web site, together with the guidelines:

http://www.bwg.admin.ch/themen/sperren/f/index.htm (French) or
http://www.bwg.admin.ch/themen/sperren/d/index.htm (German).

ACKNOWLEDGEMENTS

The guidelines on the assessment of the earthquake behavior of dams were prepared by the following working group:

Mr. W. Amberg, Lombardi Engineering Ltd, Minusio CH
Dr. C. Bossoney, Stucky Engineering Services Ltd, Renens CH
Dr. G.R. Darbre, Federal Office for Water and Geology, Bienne CH (Chair)
Dr. J. Hammer, Federal Office for Water and Geology, Bienne CH
Dr. B. Otto, Nordostschweizerische Kraftwerke, Baden CH
Dr. J. Studer, Studer Engineering Ltd, Zurich CH
Dr. M. Wieland, Electrowatt Econo Ltd, Zurich CH

The contribution of Prof. D. Giardini, Dr. N. Deichmann and Dr. D. Faeh of the Swiss Seismological Survey is also acknowledged.