Georges R. Darbre, Biel, Jost A. Studer, Zürich

Earthquake Safety of Dams

Dams are central to the industrial and agricultural development of many countries through electricity production and irrigation. They also often contribute to a significant reduction of the flood hazard to which downstream areas are exposed. At the same time, a sudden and uncontrolled release of reservoir water can have catastrophic consequences and disrupt proper functioning of the society at large. This warrants the careful – but decisive – use of advanced engineering techniques in relation with dam safety. Earthquakes are one of the many hazards considered in the corresponding safety assessments.

Damages to and collapses of buildings and bridges are observed in many earthquakes. They are, as a rule, due to the horizontal components of earthquake excitation. Dams are meant to resist horizontal loads (hydrostatic pressure), whereas buildings and bridges are not. Because of this, dams are less prone to collapse during earthquakes. This fundamental difference in structural systems also leads to the use of somewhat different techniques of earthquake analysis. Those related to dams are presented below.

Seismic input – loading conditions

Earthquakes occur suddenly and cannot be predicted. There is international agreement in designing major dams for the Maximum Credible Earthquake (MCE) evaluated on the basis of deterministic and/or probabilistic procedures depending on the information available. In Switzerland, the MCE is selected as an earthquake with a return period of 10 000 years. Such an earthquake has a 1 % probability of being exceeded in 100 years.

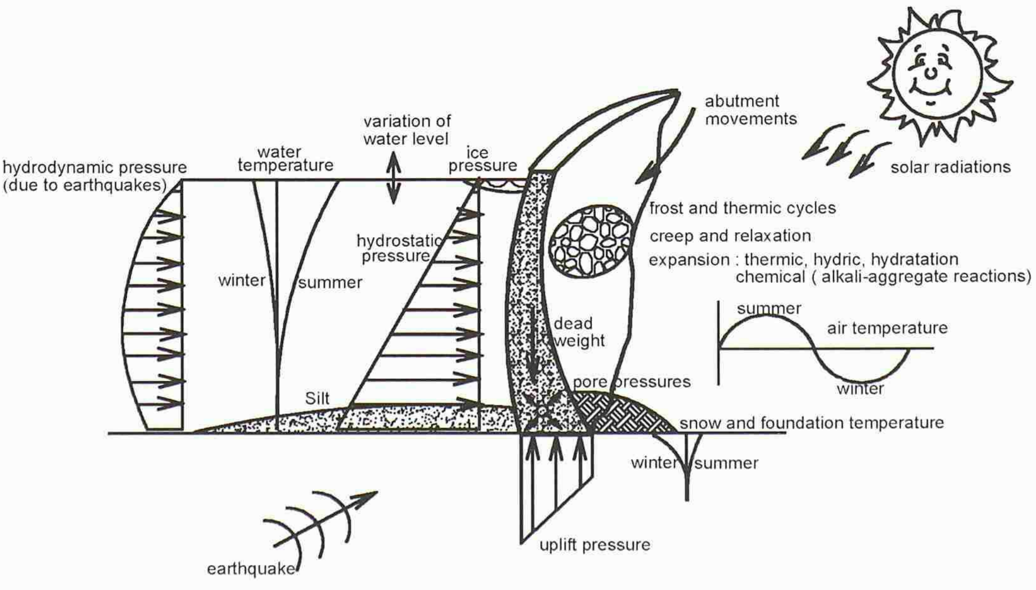
The ultimate objective is to assess the performance of a dam during and after an earthquake. An earthquake analysis is thus never disconnected from a static analysis and from the static conditions that prevail at the time of the earthquake.

The loading conditions usually considered in the structural analysis of an arch dam are depicted in Figure1 as an example. They include the dead weight of the dam concrete (the corresponding stresses and strains depend on the construction and grouting sequences, i.e. when and what portion of the arch action is mobilised), sediment (silt) pressure, water-related pressures (hydrostatic, uplift, internal, ice - all depending on the water level), temperature-induced solicitations (water, air, foundation, snow deposits, solar radiation), material-related ones (from frost and thermal cycles, creep and relaxation, expansion of various origins), abutment movements, and finally earthquake excitation including the associated hydrodynamic pressure.

Quite often though, only a few of these solicitations will significantly affect the overall integrity of the dam. For the associated verifications, it is then sufficient and customary to consider only the following load combinations:

- Construction stages
- Usual load combinations: Gravity load of dam concrete +
  - Hydrostatic loading for maximum operating water level
  - Hydrostatic loading for extreme operating water levels + Associated temperature variations + Sediment loading (+ Ice loading)
  - Extreme temperature variations + Associated hydrostatic loading(s) + Sediment loading (+ Ice loading)
- Unusual load combination: Gravity load of dam concrete + Flood loading + Associated temperature variation + Sediment loading
- Extreme load combination: The usual loadcombinations + Earthquake loading (Maximum Credible Earthquake - MCE)

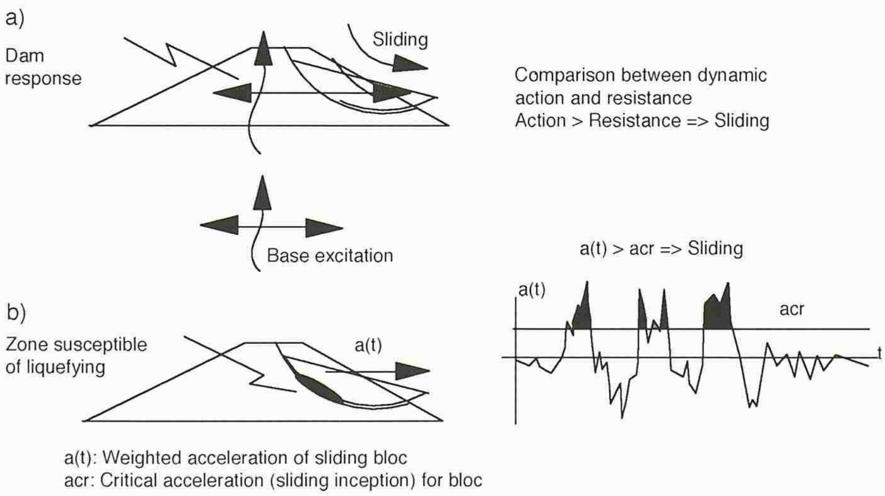
Different performance requirements are set for the various load combinations.



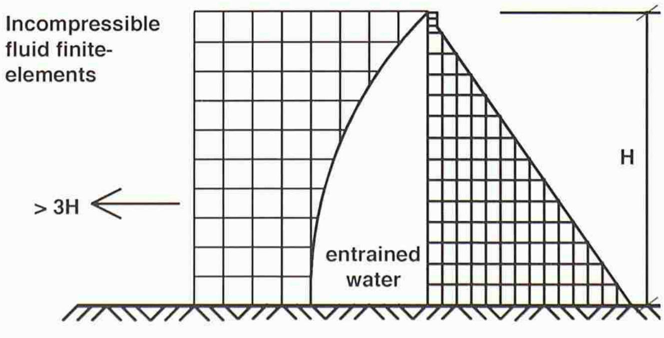
1

Structural solicitations of an arch dam (adapted from P. Léger & R. Tinawi, A bibliography on structural analysis, behaviour, and safety of concrete dams, Report No. EPM/GCS-1997-01, Department of Civil Engineering, Ecole Polytechnique, Montréal, 1997)

2
Mattmark Dam



3
Bloc sliding analysis: a) Principle; b) Implementation



4
Model of a gravity dam

Embankment dams

Analysis procedure

The earthquake analysis of an embankment dam such as Mattmark, Figure 2, is typically performed for a two-dimensional model whose geometry and characteristics are those of the central section of the dam. The analysis consists of verifying the stability of individual portions of the dam (blocs), whereby the resultant of the inertia forces acting on a bloc is compared to the resisting force along the bloc-dam interface (Figure 3a) as follows:

1.) Determine the static state of equilibrium that prevails in the dam (for example from a finite-element calculation, accounting for the construction stages and consolidation)

2.) Determine the non-linear dynamic mechanical characteristics of the dam materials from laboratory tests (modulus of elasticity, Poisson's ratio and damping, all depending on the level and rate of loading)

3.) Determine the earthquake motions and stresses in the dam by a finite-element calculation in the time-domain (equivalent-linear or elasto-plastic material-properties, uniform base excitation)

4.) Submit the test specimen of dam materials to the total stresses (static + cyclic dynamic) calculated under point 3 in various parts of the dam. Determine the increase in pore pressure and the resulting loss of shear resistance and associated strain

5.) Determine the zones of the dam susceptible of liquefying (total or partial loss of shear resistance due to the rise in pore water pressure)

6.) Perform one or several sliding bloc analyses whereby the zones susceptible of liquefying (as determined under point 5) are properly accounted for and the accelerations in the dam body (as calculated under point 3) are used. An incremental displacement of a bloc occurs when the weighted, horizontal acceleration becomes larger than the critical horizontal acceleration corresponding to sliding inception. Sliding stops as soon as the weighted acceleration returns below the critical acceleration (Figure 3b). If no sliding occurs, the permanent, remaining strains obtained under point 4 are transformed semi-empirically in dam permanent, remaining deformation.

The procedure above is typically used to analyse dams constructed of materials prone to pore water pressure build-up and to the ensuing possible loss in shear resistance (saturated sands of low and medium density). For dams built of materials whose characteristics change only very little under cyclic loading (compacted cohesive clays, dry gravely sands and very dense gravely saturated sands or rockfill), only steps 3 and 6 are usually performed.

Further simplifications are introduced for smaller dams and preliminary studies, in particular replacing the finite-element calculation (step 3) by empirical expressions for the fundamental period of vibration and the associated mode shape (the peak acceleration response is then obtained from a response spectrum) as well as by introducing expressions relating the typical number of cycles of motions as a function of earthquake magnitude in step 6.

The initial static conditions have a great influence on the mechanical dynamic characteristics of the dam materials. It is also important to recognise that the most unfavourable state of equilibrium may be the one prevailing after the earthquake because of the redistribution of the pore pressures. It is further known that hydraulic-fill dams are extremely vulnerable to earthquakes because they are prone to liquefaction (this is also true of dams constructed on loose sands).

Research areas

Knowledge of the constraints in the dam body and of the permanent deformations are essential to the assessment of the earthquake behaviour of an embankment dam that includes the issues of crest settlement (with resulting loss of freeboard), longitudinal cracks (associated with large lateral oscillations), transverse cracks (associated with large longitudinal oscillations or transverse asynchrone excitations) and cracks within the dam body (piping initiation). All cracks can lead to erosion. Also important is the assessment of the three-dimensional effects, especially in narrow valleys (significant contribution of the lateral abutments to the dam stiffness) and in the presence of vertical, longitudinal and transverse asynchrone excitations.

A geomechanical, non-linear inelastic formulation combined with a finite-element modelisation permits to address the issues above. The development of such constitutive laws for a two-phase, fluid-solid material (fully and partially saturated) is a major area of research.

Foundation-dam interaction and reservoir-dam interaction are of limited importance for embankment dams, with the exception of site effects (modification of the excitation characteristics in the subsoil) and of wave travelling effects at large dams (varying excitation across the base of the dam).

Concrete dams

State-of-practice

Modelisation of gravity dams

Gravity dams are generally analysed on the basis of a two-dimensional linear visco-elastic finite-elements model, Figure 4. The earthquake excitation is introduced as an uniform motion at the base of the dam, no variation across the base being considered (although this may be of some importance when the predominant apparent wavelengths of the earthquake are of the same order of magnitude as the base width). Three-dimensional modelling of gravity dams may be required in the presence of asynchrone transverse excitations (in particular at a dam with shear keys), longitudinal excitations and at narrow canyons.

Modelisation of arch dams

The three-dimensional geometry of an arch dam as McKay's Dam, Figure 5, is also modelled by linear visco-elastic finite-elements, Figure 6. The configuration of the grid is taken from that used in a static analysis in which it is necessary to consider the effect of the weight of the concrete that acts on the independent cantilevers before the vertical joints are grouted.

Foundation

The foundation rock is considered to be rigid at gravity dams and is modelled by finite elements at arch dams (Figure 6). No inertia is considered in the latter case as this would lead to waves remaining trapped within the foundation region, what does not occur in reality (transfer of the waves towards the outside of the region). The earthquake is introduced as an uniform ex-

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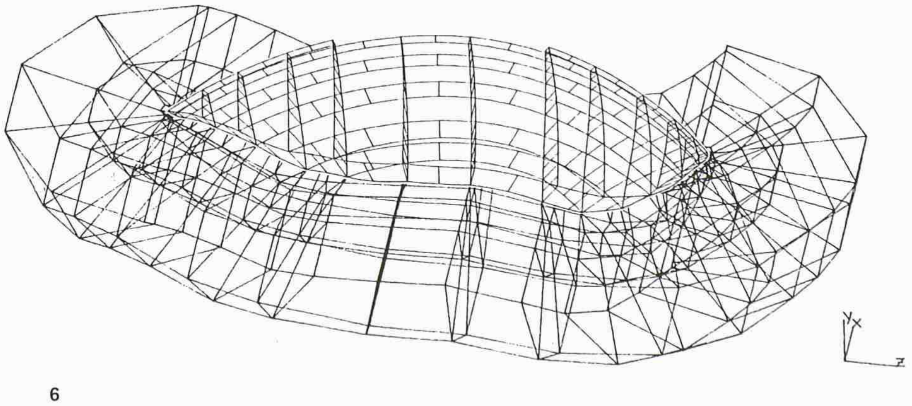
McKay's arch dam



6
Model of McKay's Dam and foundation

citing motion along the outside boundary of the rock region.

Reservoir

A water mass attached to the upstream face of the dam and entrained by its movements reproduces the influence of the reservoir on the dam. It is obtained analytically (incompressible fluid contained in a reservoir of infinite length according to the formulation of Westergaard) or by discretisation (incompressible fluid finite elements comprising a reservoir length of at least three times the reservoir depth, Figure 4).

Time integration

Integration over time is performed directly, progressing step by step while enforcing equilibrium at each step. The integration is performed for all degrees of freedom directly (direct integration) or for a limited number of generalised degrees of freedom obtained by modal decomposition.

An analysis based on the response-spectrum method, in which the peak response of each mode of vibration is read directly from a diagram, is used solely in the analysis of smaller dams and for comparison purposes. The disadvantage of such an approach lies in its approximate prediction of the maximum dam response (according to the square root of the sum of the squares of the individual modal responses) and in its lack of information on the duration of large solicitations.

Global stability

The dynamic stresses are combined with the static ones and compared to the dynamic ultimate strength of the concrete. The global stability is evaluated in an empirical way, interpreting the stresses obtained in terms of value, spatial distribution and duration. An assessment of the overall stability of the dam against sliding and against overturning is also performed.

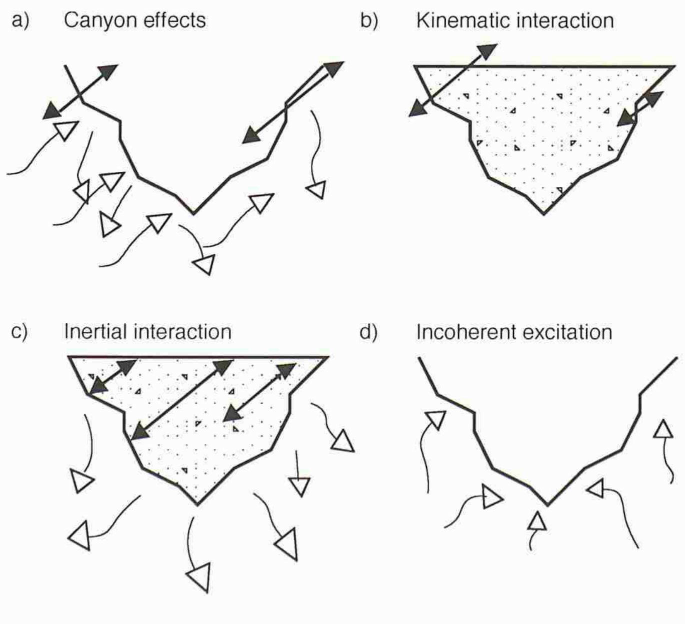
Research areas

The main areas of research stem from the following limitations of the state-of-practice:

- Non-linear effects are not considered directly. The analysis thus applies only to cases where the behaviour of the dam is essentially linear (no or few irreversible deformations or cracks).
- The influence of the flexibility of the foundation rock on the dynamic behaviour of the dam as well as the ability of the foundation to dissipate energy internally or by way of radiation are ignored (no dam-foundation interaction).
- The water mass attached to the dam is obtained for an incompressible fluid whereas water is compressible.

Non-linear behaviour

Cracks can occur during severe oscillations. At gravity dams, this is more particularly the case at the dam heel and in the vicinity of abrupt changes in geometry. At arch dams, large tensile stresses tend to develop in the arch direction in the upper central part of the dam, in the vertical direction at the base and along the abutments. Lift and grout joints also represent potential weak zones. In related research, emphasis is put on the non-linear inelastic dynamic modelling of mass concrete (in particular on fracture mechanics).



7
Dam-foundation interaction

Dam-foundation interaction

The flexibility of the foundation and its capacity to dissipate energy affect the dynamic behaviour of the dam. While the problem is relatively straightforward to solve at gravity dams where dynamic interaction coefficients can be obtained, it is more complex at arch dams. First, the topography of the valley and the inertia and energy dissipation properties of the foundation rock lead to a non-uniform earthquake excitation, and this also in the absence of a dam (canyon effects, Figure 7a). Then, assuming that the dam has no mass (flexibility only), the motion along the abutment of the dam is affected by the static resistance that the dam offers to a deformation (kinematic interaction, Figure 7b). Canyon effects and kinematic interaction are more pronounced when the significant wavelengths of the excitation are short compared to a characteristic dimension of the site and of the dam. Finally, the motion along the abutment is modified by the inertial response of the dam (inertial interaction, Figure 7c).

Further, the seismic excitation is composed of various wave trains coming from different directions that arrive in an incoherent way (Figure 7d).

All these elements are considered approximately or not at all in the established methods of analysis due to the fact that only the flexibility of the foundation is considered in the calculation and that the excitation is introduced as uniform along the external boundary of the model of the foundation rock.

Reservoir-dam interaction

The pressure exerted on the upstream face of a dam during an earthquake is affected by the compressibility of the water. The advanced solution procedures available refer to reservoirs of quasi-infinite extent, what does not apply in Switzerland. Corresponding solutions for reservoirs of finite extent are essentially non existent.

Numerical methods

Investigating non-linear effects requires an analysis in the time domain while considering interaction effects requires an analysis in the frequency-domain. Ways to overcome this - apparent - contradiction is an other area of extensive research.

Research on earthquake behaviour of concrete dams at IBK

Research on the earthquake behaviour of concrete dams at the Institute of Structural Engineering (IBK) of the ETH started in 1982 under the direction of Hugo Bachmann with the support of the Federal Office for Water and Geology (Safety of Dams). It continued up to recently. The objective of the research was to develop the analytical and numerical resources that are necessary to predict the response of gravity and arch dams to severe earthquakes, as well as to conduct the corresponding parametric studies. The major issues of concrete cracking and of dynamic foundation-dam and reservoir-dam interactions were part of the initial project. Several doctoral theses have been carried out by Hugo Bachmann's students in this area, the list of which is given below.

The authors wish Hugo Bachmann a retirement period as active and successful as his period at the ETH.

Authors' addresses:
Georges R. Darbre, Dr., dipl. Bauing. ETH, Federal Office for Water and Geology, Safety of Dams, P.O. Box 957, 2501 Bienne, *Jost A. Studer*, Dr., dipl. Bauing. ETH/SIA, Studer Engineering, Thujastrasse 4, 8038 Zürich

Doctoral theses on earthquake behaviour of dams at IBK

Modell und Berechnungsverfahren für das Rissverhalten von unarmierten Betonbauten unter Erdbebenbeanspruchung, P. Skrikerud, IBK Bericht 139, 1983

Modélisation non-linéaire du comportement du béton sous des sollicitations dynamiques, P. Chappuis, Rapport IBK 155, 1987

Talsperren-Stausee-Interaktion im Zeitbereich basierend auf der Methode der Randelemente, D. Wepf, IBK Bericht 159, 1987

A joint element for the nonlinear dynamic analysis of arch dams, J.-M. Hohberg, IBK Bericht 186, 1992

Rational Transmitting Boundaries for Time-Domain Analysis of Dam-Reservoir Interaction, B. Weber, IBK Bericht 205, 1994

Die Komplementärmethode: Ein neues Verfahren in der dynamischen Boden-Struktur-Interaktion, T. Szczesiak, IBK Bericht 224, 1996

Absorbing boundaries for the time-domain analysis of dam-reservoir-foundation systems, G. Feltrin, IBK Bericht 232, November 1997

Christian Furrer, Biel

Zum Schutz vor Naturgefahren – insbesondere Erdbeben – in der Bundesverfassung

Eine gesetzgeberische Tätigkeit des Bundes im Bereich Erdbebensicherheit ist nur zulässig, wenn sie auf eine Kompetenznorm der Bundesverfassung (BV) abgestützt werden kann. Ausgehend von der geltenden Kompetenzregelung über Naturgefahren in der Bundesverfassung werden nachstehend zwei Varianten von möglichen Verfassungsänderungen erörtert.

Die ausserparlamentarische Kommission «Plattform Naturgefahren» (Planat) unterbreitete am 14. September 1999 dem für Naturgefahren zuständigen Departement für Umwelt, Verkehr, Energie und Kommunikation (Uvek) das Massnahmenkonzept «Erdbeben» [1]. Das Konzept richtet sich in erster Linie an den Bund. Es orientiert sich an den in geltenden Erlassen und Normen vorgegebenen Schutzzielen und umfasst 18 aufeinander abgestimmte Massnahmen in den Bereichen:

- Gefährdungsanalyse und Grundlagenbeschaffung
- Rechtsetzung und Normenwesen
- Objektspezifische Massnahmen
- Ausbildung und Information
- Zivilschutz und Einsatzdienste
- Forschung

Die Überprüfung dieses Konzeptes durch eine interdepartementale Arbeitsgruppe des Bundes ist zurzeit noch im Gange. Bis Ende Jahr wird die Arbeitsgruppe dem Departement zuhanden des Bundesrates Antrag stellen für «Massnahmen zur Verbesserung auf Stufe Bund».

Die Planat stützt sich in ihrem Konzept wesentlich auf die Dokumentation «Handlungsbedarf von Behörden, Hochschulen, Industrie, Privaten zur Erdbebensicherung der Bauwerke in der Schweiz» ab. Diese ist unter der Federführung von Hugo Bachmann vom erweiterten Vorstand der Schweizer Gesellschaft für Erdbebeningenieurwesen und Baudynamik (SGEB) erarbeitet und 1998 gemeinsam mit dem Schweizerischen Ingenieur- und Architektenverein (SIA) veröffentlicht worden. Die Verfasser haben dabei im Milizsystem einen aussergewöhnlichen Einsatz geleistet und wesentlich dazu beigetragen, dass die Bundesbehörden sich der Erdbebengefährdung vermehrt bewusst geworden sind und diese jetzt ernster nehmen. Dafür gebührt Hugo Bachmann und seinem Expertenteam Dank und Anerkennung.

Die Forderung der Planat nach einer Verfassungsänderung

Die Änderung der Bundesverfassung figuriert nicht explizit im Katalog der 18 von der Planat vorgeschlagenen Massnahmen. Die Prüfung einer solchen Massnahme wird jedoch in ihrem Bericht gefordert [2]. Danach wäre die langfristig wohl wirksamste Vorsorgemassnahme zur Erdbebensicherheit in der Schweiz die Verpflichtung von Privaten, Kantonen und Gemeinden zu erdbebensicherem Bauen bzw. zur Anwendung der Vorgaben des SIA, insbesondere der Norm SIA 160 (1989) und der Richtlinie SIA 462 (1994) oder künftig des Eurocode 8. Da das Baurecht zu den traditionellen Kompetenzbereichen der Kantone und Gemeinden zählt, wäre allerdings mit Widerständen zu rechnen. Zudem müssten zahlreiche politische Fragen, z.B. zur Durchführbarkeit und Kostenwirksamkeit flächendeckender Sanierungen, geklärt werden.

Nach Ansicht der Planat sind verschiedene Varianten von Verfassungsänderungen denkbar. Beispielsweise wäre eine Bestimmung «Der Bund kann für die Neuerrichtung von Bauwerken Vorschriften über den Erdbebenschutz erlassen» mit einer verhältnismässig geringen Eingriffs-