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EARTHQUAKE SAFETY OF EXISTING DAMS

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SUMMARY

In Europe and elsewhere the economically feasible water resources have been greatly developed until the 1970s. Although large dams belong to the first structures, which have been designed systematically against earthquakes since the 1930s, the seismic safety of these dams is unknown, as most of them have been designed using seismic design criteria and methods of analysis that are considered obsolete today. The fact that no major dams have failed during earthquakes and that few lives have been lost (except in the case of tailings dam failures) may give the impression that well-designed dams are safe against earthquakes. We need to re-evaluate the seismic safety of existing dams based on current state-of-the-art practice and rehabilitate existing dams if necessary. Additionally, there are a large number of smaller dams, especially earth structures, which were built for irrigation or water supply by organisations or villagers with little experience in dam construction. Earthquake effects on these dams have rarely been considered.

1. INTRODUCTION

Large dams were among the first structures where seismic design criteria had been considered as early as the 1930s. Until 1989 when the International Commission on Large Dams (ICOLD 1989) published the guideline on 'Selecting Seismic Parameters for Large Dams' (Bulletin 72), it was common practice to design dams against earthquakes using the pseudo-static approach typically for a horizontal acceleration of 0.1 g. In the same publication the concept of two design earthquakes was introduced for dams, i.e. the operating basis earthquake (OBE) and the maximum design earthquake (MDE) or maximum credible earthquake (MCE).

The milestone in the seismic analysis of dams was the 1971 San Fernando earthquake in California where damage was caused to embankment dams (San Fernando dams) and also to an arch-gravity dam (Pacoima dam). Although a few dams had already been analysed using modern methods of dynamic analysis (concrete dams: linear-elastic dynamic analyses of dam-reservoir-foundation models; embankment dams: equivalent linear method of analysis) from 1971 to 1989, these analyses were mainly carried out for the re-analysis of existing dams as after the 1970s relatively few new dams were built in Western countries. For the new dams built in less-developed countries during this period mainly the old seismic design criteria were used except for dams in some regions of very high seismicity. Today's minimum seismic design criteria are those given in ICOLD Bulletin 72. This guideline is currently under revision. However, the basic seismic safety concept that a dam with a large damage potential must be able to resist the strongest ground motion to be expected at the dam site will stay.

Some 245 earthen dams – mainly small dams for water supply and irrigation - were damaged by the Bhuj earthquake of January 26, 2001 in Gujarat, India as a result of liquefaction. A concrete weir was also severely damaged by fault movements and ground shaking during the September 21, 1999 Chi-Chi earthquake in Taiwan (Fig. 11). The Sefid Rud buttress dam in Iran is one of the modern-type dams, which during the 1990 Manjil earthquake in Iran has been subjected to a ground motion that could be expected during an MCE. This case is not very well known among dam engineers (Fig. 1).

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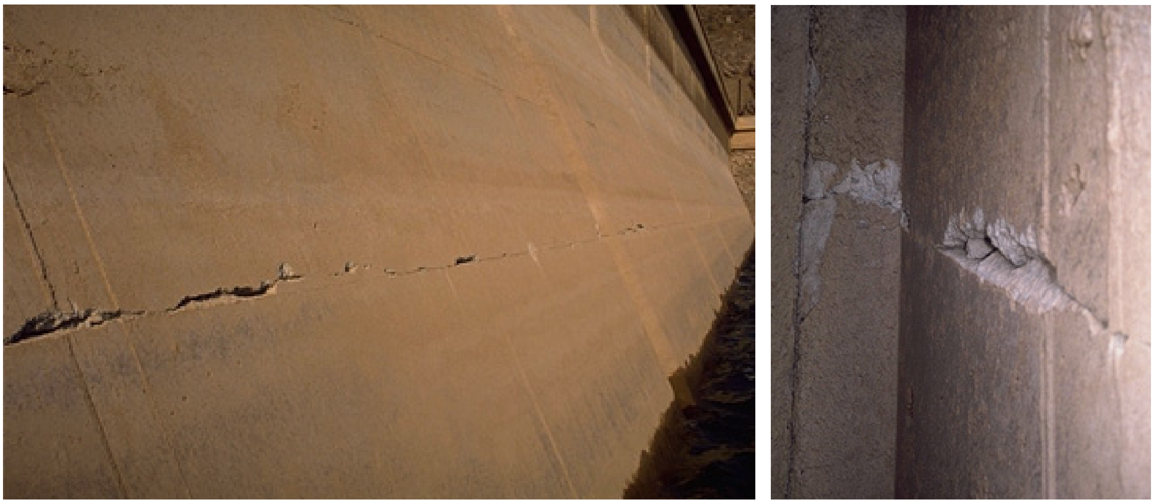

Fig. 1: Horizontal crack at lift joints in Sefid Rud buttress dam caused by 1990 Manjil earthquake in Iran (left: crack at upstream face; right: crack in web of buttress at downstream face)

Strong earthquakes have also occurred in Iran in 2003, Sumatra in 2004, Kashmir in 2005 and several in Japan. Although such ground motions might also cause problems to dams no serious damage was observed. These events have shown that the earthquake hazard continues to be a serious threat to dams.

The largest ground shaking at a dam site caused by a strong shallow focus earthquake can greatly exceed the old pseudostatic design acceleration of 0.1 g. The peak ground acceleration (PGA) on rock can reach values of up to 1.0 g in the epicentral region of a shallow focus earthquake with a magnitude of around 6.5; therefore, there is a need to explain the discrepancies between measured PGA values and those used for the design of a dam. Although the PGA is not representative for the severity of earthquake ground shaking it is still used as a characteristic value by most dam engineers. A trend for higher PGA values of the ground motions caused by strong earthquakes such as the MDE and MCE can be noticed especially in regions of moderate seismicity, like for example in Switzerland.

A lot of know-how exists already on the seismic behaviour of dams. It is necessary that this information is fully used by the dam community. It is still much cheaper to make a dam to perform well during an earthquake in the design phase than having to upgrade it later. There is also the conviction of some people that a design must be safe when a similar design has already been made repeatedly in the past. However, we have to also recognize that (i) a design that has been done wrong ten times in the past does not automatically become correct when carried out in the same way the next time, and (ii) designs of structures to resist extreme loads may never have been tested.

The design of a dam, which was considered as safe at the time it was approved may not be safe forever. This may be contradictory to the general opinion of owners and users of most buildings and structures. As earthquake engineering is still a relatively young discipline, design criteria, methods of analysis, design concepts etc. may be subject to changes especially when a large dam, designed according to the current state of practice, should be severely damaged during an earthquake. Thus there is a need for periodic checks of the seismic design criteria and the earthquake safety of large dams (and other structures as well), i.e. budgets for periodic seismic safety checks must be considered. In general, dam owners and operators are reluctant to perform such checks unless there are laws and regulations and a dam safety organization, which has the authority and means to ensure that the rules are followed. Again, the perception that what has been considered as safe once will remain safe forever is a dangerous misconception.

2. SEISMIC ACTIONS ON DAMS

Earthquakes are multiple hazards, which include ground shaking, fault movements, mass movements into the reservoir and water waves in the reservoir. Ground shaking – the main action considered by engineers - affects all structural elements and components of a dam project including the dam, foundation, safety devices, pressure system, appurtenant structures, underground works, hydromechanical and electromechanical equipment etc. Therefore all these elements have to be designed or checked for their earthquake resistance and safety. Generally, engineers, geologists, mechanical and electrical engineers etc. are mainly looking into their specific problems. This tendency is even more pronounced among researchers who are focussing on single subjects. Thus it is quite likely that (i) some important issues are overlooked, (ii) too much weight may be given to less important aspects, or (iii) different seismic design criteria are used by different professions.

As the earthquake safety of many dams, which were not designed against earthquakes or designed based on outdated seismic design criteria and methods of analysis, is unknown and new dams – mainly small ones – are being built by organisations, whose experience in dam construction is insufficient, it is important to reach the people responsible for the safety and operation of these projects.

3. SEISMIC SAFETY ASPECTS OF DAMS

3.1 Earthquake Safety Concept

The main safety concern is the failure of a dam and the uncontrolled release of the reservoir water with flood consequences (loss of life, economical damage, environmental damage etc.), which will usually exceed the economical damage to the dam. Therefore, for the seismic risk assessment of a dam, full reservoir is the critical situation.

Basically, the seismic safety of a dam depends on the following factors:

1. Structural Safety: strength to resist seismic forces without damage; capability to absorb high seismic forces by inelastic deformations (opening of joints and cracks in concrete dams; movements of joints in the foundation rock; inelastic deformation characteristics of embankment materials); stability (sliding and overturning stability), etc.
2. Safety Monitoring: strong motion instrumentation of dam and foundation; visual observations and inspection after an earthquake; data analysis and interpretation; post-earthquake safety assessment etc.
3. Operational Safety: Rule curves and operational guidelines for post-earthquake phase; experienced and qualified dam maintenance staff, etc.
4. Emergency Planning: water alarm; flood mapping and evacuation plans; safe access to dam and reservoir after a strong earthquake; lowering of reservoir; engineering back-up, etc.

In general, dams, which can resist the strong ground shaking of the MCE, will perform well under other types of actions.

In the subsequent sections, the emphasis is on the structural safety of dams, which can be improved by (i) changing the dynamic behaviour and seismic response of the dam, and (ii) by reducing the vulnerability of the dam. These measures are referred to as structural measures. Safety monitoring, operational safety and emergency planning are non-structural measures and will not be discussed.

3.2 Seismic Design and Performance Criteria

For the seismic design of dams, abutments and safety relevant components (spillway gates, bottom outlets, etc.) the following types of design earthquakes are used (Wieland 2005):

1. Operating Basis Earthquake (OBE): The OBE design is used to limit the earthquake damage to a dam project and, therefore, is mainly a concern of the dam owner. Accordingly, there are no fixed criteria for the OBE although ICOLD has proposed an average return period of ca. 145 years (50% probability of exceedance in 100 years). Sometimes return periods of 200 or 500 years are used. The dam shall remain operable after the OBE and only minor, repairable damage is accepted.

2. Maximum Credible Earthquake (MCE), Maximum Design Earthquake (MDE) or Safety Evaluation Earthquake (SEE): Strictly speaking, the MCE is a deterministic event, and is the largest reasonably conceivable earthquake that appears possible along a recognized fault or within a geographically defined tectonic province, under the presently known or presumed tectonic framework. But in practice, due to the problems involved in estimating of the corresponding ground motion, the MCE is usually

defined statistically with a typical return period of 10,000 years. Thus, the terms MDE or SEE are used as substitutes for the MCE. The stability of the dam must be ensured under the worst possible ground motions at the dam site and no uncontrolled release of water from the reservoir shall take place, although significant structural damage is accepted. In the case of significant earthquake damage, the reservoir may have to be lowered.

Historically, the performance criteria for dams and other structures have evolved from the observation of damage and/or experimental investigations. As mentioned above, the performance criteria for dams during the OBE and MCE/SEE are of very general nature and have to be considered on a case-by-case basis.

A special feature of large storage dams is reservoir-triggered seismicity (RTS). Sometimes a special RTS design earthquake was defined. However, in view of the fact that a dam must be able to resist the MCE ground motion, it is not possible that the maximum ground motion caused by RTS exceeds that of the MCE. Moreover, RTS is linked with the initial phase of reservoir operation and decreases with time. Therefore, it is not a real safety problem for the existing dams.

In view of the large uncertainties in predicting the seismic behaviour of dams it is strongly recommended to increase its resilience to earthquake loading rather than trying to reduce the uncertainties in the seismic hazard, the scatter in the material properties or to use more sophisticated methods of seismic analyses, which incorporate all kind of features such as e.g. dynamic dam-soil interaction effects etc.

3.3 Seismic Risk Considerations

The requirement that the dams with a large damage potential shall be able to withstand the ground motion caused by the MCE or the 10,000-year SEE is a logical and consistent requirement as the same dams have to be able to safely release the probable maximum flood (PMF) or the 10,000 year flood.

Strong earthquakes are rare events, especially in regions of low to moderate seismicity, and there are great uncertainties involved in the estimation of the maximum ground motion at a dam site. The discrepancies between design accelerations used for older dams and the PGA value of the SEE can be of the order of a factor of 5 or more.

In regions of moderate seismicity, floods are generally considered as the dominant natural hazard. A recent study in Switzerland has, however, shown that about 50% of the risk from the natural environment is caused by earthquakes, and flooding is less than one third of that. The main portion of the seismic risk originates from the strongest earthquakes. Due to the very low probability of occurrence of destructive earthquakes, the earthquake risk has been underestimated and it has taken quite some time to realise this fact. This is a general problem with low probability and high impact hazards.

4. UNIFORM APPLICATION OF DESIGN CONCEPTS BY DAM, HYDROMECHANICAL AND ELECTROMECHANICAL ENGINEERS

Civil, hydromechanical and electromechanical engineers etc. have different guidelines for the seismic design of structures and equipment respectively. In many cases, a value of 0.1 g was used irrespective of the location of the equipment within a dam. In the nuclear industry the so-called floor response spectra have been used for a long time, which serve as the seismic input for the equipment design. In dams, the same concept has to be used. Secondary structures and equipment attached to or located in the dam have to be designed for the support motion acting at the location of these secondary structures. Depending on the safety class of the equipment they may not have to be designed for the MCE.

Equipment or secondary structures located on the crest of concrete dams are exposed to high vibration levels, as minor earthquakes can cause amplifications of the ground motion (PGA) at the crest by factors of up to 10. For example, on August 8, 2005 a moderate near-field earthquake has caused peak accelerations on the crest of the 180 m high Emosson arch dam in Switzerland of over 0.5 g (PGA at base of dam: ca. 0.05 g).

The spillway rehabilitations are a direct consequence of dam and hydromechanical engineers probably not being aware of the dynamic amplifications of dam vibrations at the crest. The spillway piers on the crest of the

Whakamura and Roxburgh gravity dams in New Zealand were originally designed for 0.1 g. Under the effect of the SEE, peak crest accelerations of 1.9 g and 1.8 g are expected respectively (Fig. 2; Foster and Black, 2003). This large difference in design accelerations also shows that the problems of earthquake safety are often not a question of optimising safety factors by one decimal place but having to change the structural concept in order to satisfy the minimum safety demands.

Fig. 2: Seismic strengthening of spillway gate structure located on the crest of the 56 m high Whakamura gravity dam in New Zealand (left: original design of 1956 based on pseudostatic acceleration of 0.1 g; right: strengthened structure with design acceleration of 1.9 g (Foster and Black, 2003).

5. EARTHQUAKE SAFETY OF SMALL DAMS

Irrigation and water supply dams are usually earth dams with a height of less than 15 m, the limit used by ICOLD for defining large dams. They are often built by organisations and local communities, who have little or no experience in dam design and construction. It has to be pointed out that rural dams are different from the well-engineered large dams for hydropower generation.

The Bhuj earthquake of January 26, 2001 has shown that these dams are vulnerable to earthquake action. The dams have been damaged mainly by liquefaction causing cracks, deformations and settlements (Figs. 3 and 4). Due to the fact that the reservoirs were practically empty at the time of the earthquake, no catastrophic dam failure occurred.

Fig. 3: Embankment dam damage caused by the 2001 Bhuj earthquake in India (about 245 damaged or deficient dams needed repair and seismic upgrading after the earthquake)

The rural dams, which are not earthquake proof, may fail even under moderate earthquakes that occur much more frequently than the MCE. Moreover, it has to be considered that a strong earthquake can cause damage over an area of hundreds of square kilometres, where several rural dams are located storing water of similar volume as a large dam. Therefore, in view of the fact that the failure probabilities of rural dams are orders of magnitude higher than that of well-engineered large dams and in view of the total amount of water stored behind rural dams, it can be concluded that the total earthquake risk of a distributed system or cascade of small dams may actually be higher than that of a large dam. In general, one would conclude that the concept of many small dams is safer than a single large dam. Based on the experience during the Bhuj earthquake, it has to be assumed that the earthquake safety of small rural dams is often inadequate and by far inferior to that of well-engineered large dams.

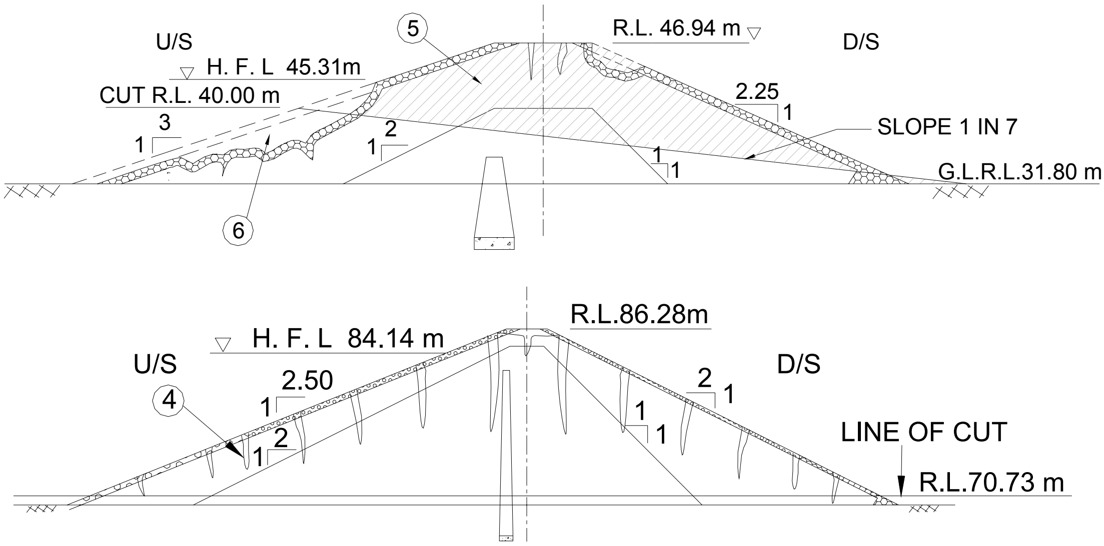

Fig. 4: Typical earthquake damage caused by the 2001 Bhuj earthquake in India (Patel et al., 2003). Suvi Dam (top): major sliding movement (6) at the upstream slope of the dam, the zone of the dam marked by (5) was removed and rebuilt; Chang Dam (bottom): Dam suffered major longitudinal and transverse cracks and large settlements, the dam was removed in the central portion down to elevation 70.73 and shall be reconstructed.

6. SEISMIC SAFETY EVALUATION OF EXISTING DAMS

There are two cases, which call for the safety evaluation of existing dams: (i) when a strong earthquake has occurred and strong motion instruments have recorded strong shaking in a dam and a post-earthquake inspection has revealed some damage, and (ii) when the seismic design criteria or seismic performance criteria have changed and/or new developments have taken place (a) in the seismic hazard assessment, (b) in the methods of seismic analysis, or (c) in the dynamic behaviour of materials, etc.

6.1 Embankment Dams

The basic steps for the seismic re-evaluation of the seismic safety of embankment dams are as follows:

- Determination of main parameters of the safety evaluation earthquake (i.e. response spectrum, PGA, duration of strong ground shaking);
- Estimation of dynamic material properties based on static and dynamic laboratory tests or information extracted from the literature (results of standard penetration tests can also be used);
- Dynamic analysis of a two- or three-dimensional finite element model of the dam-foundation system using, e.g., the equivalent linear method;
- Assessment of pore pressure build-up (liquefaction analysis for certain foundation conditions or materials in hydraulic fill dams);
- Calculation of permanent displacements of potential sliding masses along the dam slopes by, e.g., the Newmark sliding block analysis;
- Seismic settlement analysis;
- Estimation of the freeboard reduction during the safety evaluation earthquake; and

- Seismic safety assessment based on the results of the earthquake analysis.

6.2 Concrete Dams

In the case of concrete dams, the basic steps for the seismic safety re-evaluation are as follows:
- Determination of main parameters of the safety evaluation earthquake;
- Estimation of dynamic material properties of mass concrete and foundation rock;
- Modelling of joints whenever necessary;
- Dynamic analysis of a two- or three-dimensional finite element model of the dam-reservoir-foundation system;
- Dynamic stability analysis of concrete blocks separated by joints and/or cracks;
- Dynamic foundation stability analysis; and
- Seismic safety assessment based on the results of the earthquake analysis.

7. SEISMIC SAFETY EVALUATION AND REHABILITATION

7.1 Dam Safety Classification

Morison et al. (2003) have developed a method for the seismic safety evaluation of over 90 dams (mainly concrete structures) in Scotland. For seismic risk classification, the reservoir volume, the dam height, the downstream population at risk, and the downstream damage potential were considered. A simple system was used to calculate the structural vulnerability index of a dam, which is used to determine the dam category (four categories are used). The main factors chosen to define seismic vulnerability were:
- Dam height;
- PGA at dam site;
- Type of dam, with additional adjustments for key risk factors for particular dam types;
- Dam foundation conditions; and
- Age and condition of the dam.

Such relatively simple classification systems are very useful in performing a fast screening of small and large dams.

7.2 Rehabilitation, Strengthening and Repair of Damaged Concrete Dams

There are only few case histories where a concrete dam has suffered severe damage as a result of earthquake-induced ground motions (Wieland et al. 2003). The best-known examples are the Hsinfengkiang buttress dam in China, the Koyna gravity dam in India (Fig. 5), the Sefid Rud buttress dam in Iran (Figs. 1 and 6), and the Shih-Kang concrete weir in Taiwan (Fig. 11).

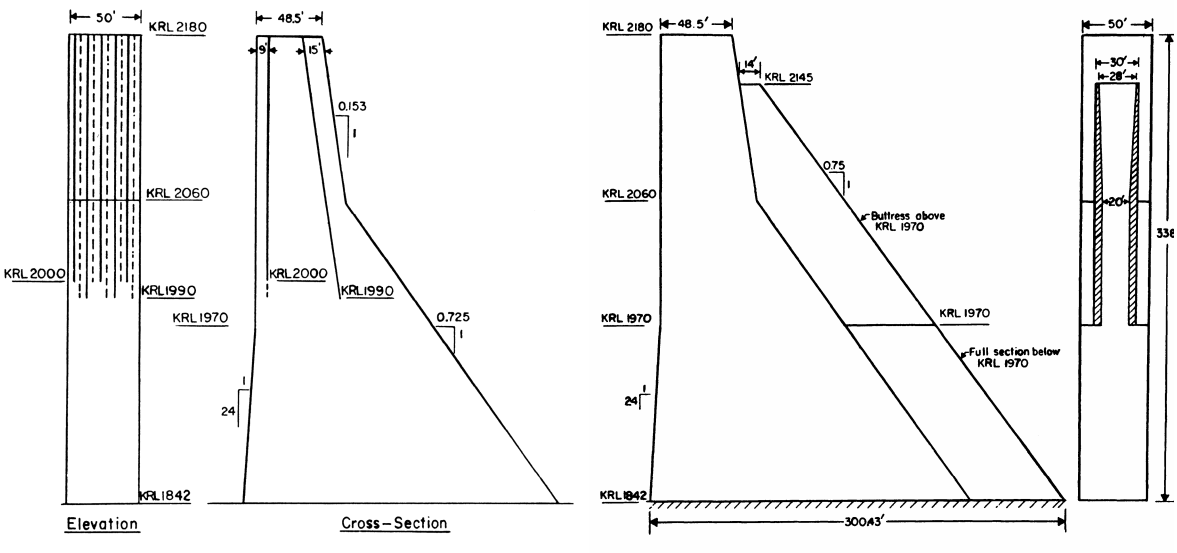

Fig. 5: Repair and strengthening of non-overflow monoliths of Koyna gravity dam by post-tensioned anchors (left) and buttresses (right) (Wieland et al. 2003)

In the first three cases the damage pattern was similar, i.e. cracks appeared near the kink at the downstream face of the dams. Concrete dams will experience cracking mainly along horizontal working joints and some of the detached blocks may undergo limited sliding movements. The structures could be repaired and they are in operation, but the repairing techniques differed somewhat. However, no further damaging earthquakes have occurred at these sites and the efficiency of the repair work could not be evaluated directly. These cases demonstrate the significant resiliency of concrete gravity and buttress dams to earthquake loading under the most severe conditions.

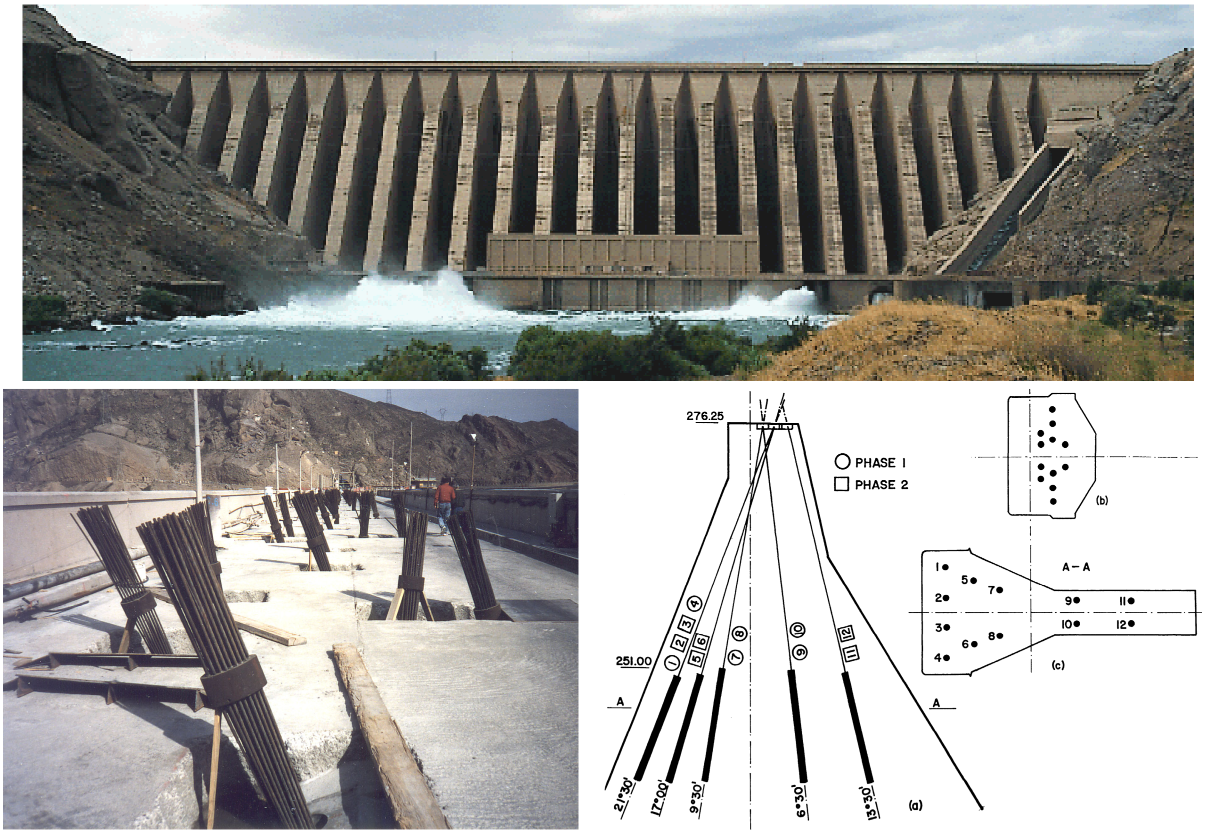

Fig. 6: Repair work at Sefid Rud buttress dam (top and left) and arrangement of twelve post-tensioned anchors in buttresses 8 to 23. (a) transverse section, (b) top elevation, (c) Section A-A (right) (Wieland et al. 2003)

In the case of the Shih-Kang weir, which was located on an active fault, the main damage was caused by fault and surface movements. Unless special provisions are made, e.g. a joint that enables a certain amount of displacement, concrete dam blocks will rupture completely.

7.3 Dam safety evaluation in California

In California more than 1200 dams are currently under state supervision and the federal government owns an additional 175 dams in the state. The seismic safety of these dams was checked. As a result of this comprehensive evaluation 116 dams were identified as being deficient, including some severely damaged by earthquakes (Babbitt 2003). Thus safety improvements were required. The improvement ranged from various structural strengthening (berming, buttressing, additional foundation treatment) to permanent or temporary storage restrictions, to dam removal in most serious cases (Table 1).

Reservoir storage has been reduced to improve safety as soon as analyses predicted unsatisfactory seismic dam performance. Storage restrictions were usually not considered as permanent solutions, unless gates had been removed from outlets, spillways crests lowered, or other alterations made to assure that the reservoir water surface does not rise above the restricted level.

Two typical examples of dam strengthening and rehabilitation of an embankment and multiple arch dam are shown in Figs. 7 and 8, respectively.

Table 1: Seismic improvements to 116 dams in California (Babbitt 2003)

Buttresses added or slopes flattened on earthfill dams	34
Freeboard increased by adding embankment	3
Crack stopper zones added	6
Foundation and/or embankment materials removed and replaced	11
Vibroflotation – vibracompaction or deep dynamic compaction	4
Foundation grouting – drainage or cutoff wall construction	11
Diversion conduits plugged	2
Concrete dams buttressed with concrete	7
Multiple arch dams cross braced, strutted or reinforced	4
Post-tensioned tendons installed	3
Freeboard increased by lowering spillway weirs, removing spillway gates, etc	27
Dams removed (some replaced by tanks)	5
Replacement dams constructed	10
Reservoirs maintained empty (some provide short duration flood detention)	7
Permanent storage restrictions	12
Storage restrictions until permanent improvement	36
Outlet works rehabilitations	21
Spillway replacement or rehabilitation	2
Total Improvements	205*

*Several dams have more than one type of improvement.

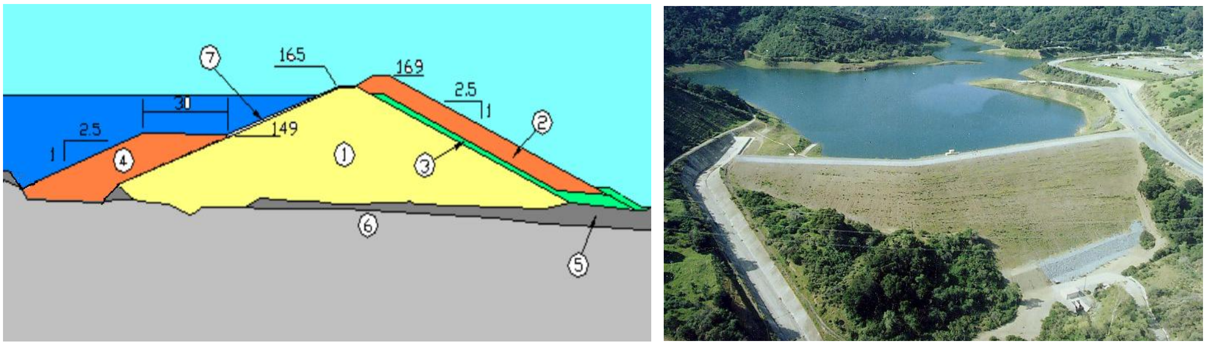

Fig. 7: Rehabilitation of Stevens Creek embankment dam: different measures for seismic strengthening of the dam at the up- and downstream faces of the dam have been used

Fig. 8: Seismic strengthening of Weber multiple arch dam in California: strengthening of abutments by RCC block (left) final stage; (right) construction state (Photos D. Babbitt).

In various parts of the world, similar dam safety evaluation programs and actions are to be expected in the future. This is not only of high importance for countries with high seismicity but also for regions with moderate to low seismicity as earthquake action may have been ignored at all in such places, thus the earthquake vulnerability of the dams may be higher than that of dams in highly seismic regions.

8. SOME EXAMPLES AND OBSERVATIONS

8.1 Earthquake Safety as the Main Safety Concern for Large Dams

Tehri dam is a rockfill dam with central clay core and with a height of 265 m. It is one of the world's largest embankment dams and is located in the foothills of the Himalayas in India's Uttaranchal Pradesh province. Seismicity is very high and close to the dam a major active fault is located, which has the potential of producing large earthquakes. When the dam was designed some 25 years ago the engineers considered a design earthquake with a 'standard' pseudostatic acceleration of 0.1 g as adequate. Since the start, this project has attracted much attention mainly due to the resettlement and environmental reasons but also because of its earthquake safety and the likelihood of reservoir-triggered seismicity. Therefore, and in view of new developments during the very long design and construction phases of this project, the seismic design of the dam was checked by using more severe seismic design criteria, using more sophisticated methods of dynamic analysis, and by taking special measures to reduce the dam's seismic vulnerability.

At present the reservoir is being filled. Following the October 2005 Kashmir earthquake in Pakistan new concerns appeared in the newspapers, in which this event was interpreted as a precursor for an even stronger earthquake in the Himalayas, which could directly affect Tehri dam.

Because of the large uncertainties in estimating the design ground motions at a dam site, there is always some reason for questioning the earthquake safety of a large dam. Because of that, the dam (or project) owner is ill advised to select low design ground motion values for the MCE and trying to defend them. One must also keep in mind that the design criteria have always gone up – they have never been reduced.

8.2 Change in Assessment of Seismic Environment

Khao Laem dam located in Kanchanaburi province in Thailand, close to the Burmese border, is a concrete-face rockfill dam (CFRD), which when completed in the early 1980s was one of the largest CFRDs in the world. Local and regional seismicity in this remote part of Thailand was hardly known and the dam was designed against earthquakes with a pseudostatic acceleration of about 0.1 g. In addition to that, CFRDs were considered as the best dams against earthquakes.

During construction of the dam a fault was found in the footprint of the dam. At that time the fault was considered as inactive by the responsible geologists as there was no instrumental data, which would prove that it is active. However, there were doubts about this assessment. During the filling and subsequent operation of the reservoir, reservoir-triggered seismicity was observed. Because of these concerns and observations the owner carried out an independent seismic hazard study in the late 1990s assuming that the fault is potentially active – this assessment is now generally accepted among local geologists – very high PGA values were estimated. Therefore, a seismic safety evaluation is needed. In such a situation the dam owner or the dam safety authorities have two options. In the first option, because of the very sparse data that is available for the estimate of MCE ground motions, additional measurements are requested, which for rare earthquakes will take a long time until much better results can be provided. In the second option, which can be considered as an engineering approach, it is determined how much fault movement and ground shaking the dam can safely withstand.

It is obvious that in order to cope with the seismic dam safety concerns of the population living in the downstream area of a large dam, it is much better to choose the second option. If the seismic resistance should be inadequate then some of the actions described in the previous sections must be taken. In the short term, if the safety is inadequate then restrictions on the reservoir level must be imposed.

What can we learn from these two cases and many others is that seismic safety assessments have to be made in such a way that the seismic capacity of a dam is evaluated (i.e. how much seismic loading it can sustain) rather than the analysis of the seismic behaviour under an earthquake, which may have to be increased in the near future because of new developments. By doing that a new seismic safety assessment may be avoided if the seismic design criteria are changed.

8.3 A Case in Central Europe

The 117 m high Mattmark dam rests on a soil layer with a maximum depth of 88 m (Fig. 9). The dam is situated in the highest seismic zone of Switzerland. In connection with a planned increase of the full supply level of the reservoir, a comprehensive seismic safety evaluation was carried out based on the Swiss earthquake guidelines for dams (BWG 2003). The dynamic analysis was performed using a two-dimensional finite element model of the dam-foundation system. The input motion consisted of three different sets of spectrum-compatible artificial accelerograms with horizontal and vertical peak ground accelerations of 0.42 g and 0.28 g respectively, corresponding to the safety evaluation earthquake (SEE). Originally the dam was designed for a seismic coefficient of 0.1.

The core and the shell of the dam are also made of morainic materials. In the case of the core, coarse-grained components larger than 10 cm were removed and the fill was compacted. The shell was built without any compaction. In order to facilitate the foundation grouting works, an inclined core was selected. The dynamic material properties were selected on the basis of the results of static and dynamic laboratory tests and information available in the geotechnical literature.

The analysis showed that shallow slides could move 2 m to 3 m during the SEE (Wieland and Malla 2002). For deeper slides, the maximum displacement would be less than 80 cm. From the safety point of view, the deeper slides are more critical, as they cut through the whole core, whereas the shallow slides do not. The seismic settlements were estimated based on the reduction of the shear stiffness of the various materials during the SEE. The freeboard remaining after the sliding displacements and the seismic settlements caused by the SEE should be sufficient after the earthquake. The well-graded core material taken from a moraine and the wide filter layers will prevent any piping effects.

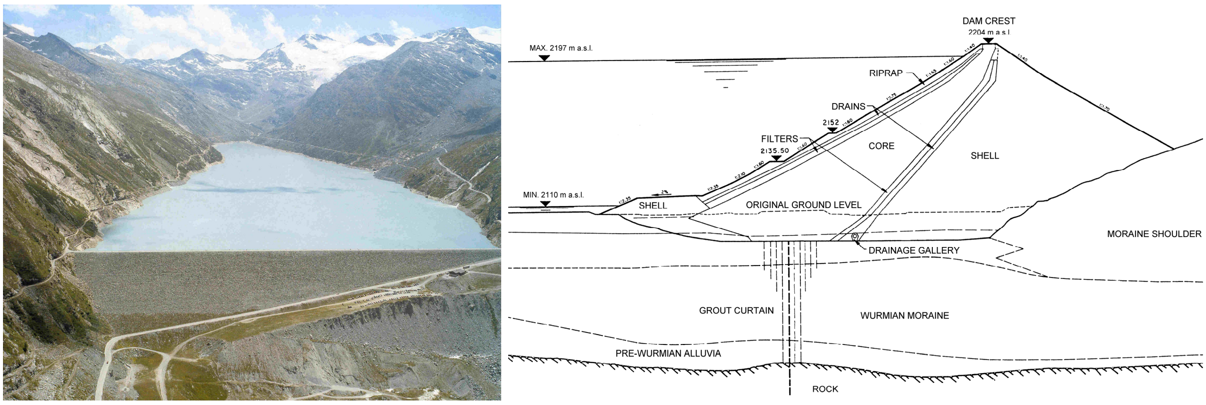

Fig. 9: Mattmark embankment dam: aerial view (left) and typical cross-section (right)

Reduction of freeboard
The earthquake-induced displacement of a shallow (close to dam surface) sliding block could be as high as 3 m, but this would not lead to a freeboard reduction, as the sliding movement does not cut through the core. The largest reduction of the freeboard, due to the sliding displacement of a deeper block cutting through the whole width of the core, was estimated to be approximately 0.8 m. When the estimated seismic settlement of about 0.75 m is also added, the total reduction of the freeboard would be of the order of 1.6 m. For the future maximum reservoir level the available freeboard will be 5 m. Although the top of the core is about 1.7 m below the crest level, there would still be sufficient freeboard after the SEE.

Danger of internal erosion
The combined thickness of the filter and drainage layers on the upstream side of the core increases from 2.6 m at the top to 5.9 m at the base. The combined thickness of the filter and drainage layers on the downstream side increases from 4 m at the top to 6 m each at the base. According to the earthquake guidelines the sliding displacements should not exceed 50% of the combined thickness of the filter and drainage layers. The maximum displacement along a slip surface cutting across the filter and drainage layers below the reservoir level is 0.8 m, which is about 20% to 30% of the combined thickness of these layers at the top of the dam. The integrity of the filter and drainage layers should be, therefore, adequate even after the earthquake-induced sliding movements.

Moreover, the morainic core material with uniform gradation has self-healing properties, which ensures that a leak does not develop along the slip surface.

The main conclusions of the seismic safety evaluation of Mattmark dam are (i) that the dam is still safe although the seismic design criteria have been changed from a seismic coefficient of 0.1 to a PGA of the SEE of 0.42 g, and (ii) that new methods of analysis and new performance criteria must be used to assess the earthquake safety of the dam. The earthquake safety would not be sufficient if the new seismic design criteria would be used simultaneously with a pseudostatic analysis.

9. SWISS GUIDELINES ON ASSESSMENT OF EARTHQUAKE BEHAVIOR OF DAMS

9.1 Basic Concepts

The current version of the Swiss earthquake guidelines for dams is from 2003 (BWG 2003; Darbre et al. 2002). The objective is to protect people, environment and property in the downstream area of large dams. A similar level of protection at all dams should be provided.

The safety evaluation earthquake (SEE) serves as basis for the assessment. It is required that, under that earthquake, 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. Depending on the risk three dam classes are defined with average return periods of the SEE of 1,000 years (class 3), 5,000 years (class 2) and 10,000 years (class 3). The PGA values are obtained from a table and the acceleration response spectra are taken from Eurocode 8 (Part 1) scaled with the PGA. For time history analyses spectrum-compatible artificial accelerograms can be used. The duration of strong ground shaking (T_s in seconds) of at least 10 s can be determined from the following relation:

$$T_s = 5 + 50\ PGA/g$$

When a time domain analysis is conducted, at least three sets of statistically independent time histories must be considered, whereas the strong-motion duration may vary by ± 5 seconds in two of them. Each set is composed of three earthquake components (2 horizontal and 1 vertical).

Under this approach, damages that do not result in uncontrolled release of water nor to non-restorable functionality of safety-relevant appurtenant structures and components are accepted.

There are also no serviceability requirements (operating basis earthquake), although it is in the interest of the owner of targeting one. In fact it is unlikely that a dam that cannot operate after a moderate earthquake will fulfil the SEE requirements.

It is stressed that the objectives and requirements put forward in the guidelines are minimal ones. They can be replaced by ones that are demonstrated to be equivalent or more stringent.

The guidelines are largely a formalization of the recent dam engineering practice in Switzerland with regard to the assessment of earthquake safety.

9.2 Declaration of Conformity and Technical Qualifications

It is required that the assessment be fully documented. It shall contain a declaration of conformity personally signed by the lead engineer in which it is confirmed that the requirements of the guidelines are satisfied in full.

It is also required that the lead engineer possesses the appropriate knowledge and experience to carry out the assessment. This is translated into the following required qualifications:

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

9.3 Criteria for Embankment Dams

The assessment is based on a two-step analysis. At first, the pseudostatic sliding stability of individual dam parts is systematically evaluated. Is the stability not guaranteed then a dynamic sliding block analysis is performed in the second step. It must then be demonstrated that specific displacement limits are satisfied and the overall dam stability guaranteed. It must in particular be demonstrated that the freeboard remains sufficient (no dam overtopping) and that the drainage and core layers be able to fulfill their purpose.

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

Table 2: Modelling requirements for existing embankment dams (Darbre 2002)

	Material properties and investigation methods	Modeling and calculation methods
Class 3 embankments	Static properties Obtained from construction documents or cross comparisons	Simplified stability analysis with pseudostatic earthquake load, horizontal action alone Simplified calculation of sliding displacements if necessary
Class 2 embankments	Static properties, possibly dynamic properties Obtained 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 Static and dynamic properties obtained from construction documents (from tests if none available)	2D static and dynamic FE-calculations for dam response Simplified dynamic stability analysis based on calculated dam response (horizontal and vertical excitation) Simplified calculation of sliding displacements if necessary

9.4 Criteria for Concrete and Masonry Dams

It is required that both a stress and a stability assessment be performed, as well as additional assessments related to appurtenant structures and components, foundation and reservoir banks. In the stress analysis, the stresses (or forces) obtained from the combined static and dynamic loads are compared with the strength of mass concrete or masonry. For earthquake actions, an increase in the dynamic tensile strength of 50% with respect to the static one is allowed. 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.

For the dynamic analysis a damping ratio of 5% of critical is specified for the SEE.

9.5 Criteria for Run-of-River Dams and Weirs

River dams are composed of a submerged structure with or without a large structure above water (e.g. tall piers supporting a service bridge with heavy machinery, Fig. 10). They may be made of masonry, concrete, reinforced concrete, steel. This variety in structural systems and construction materials has led to the recommendation to use other regulations and guidelines, taking into account the fundamental philosophy of uniform risk and the resulting dam classification (and thus return period and modelling details).

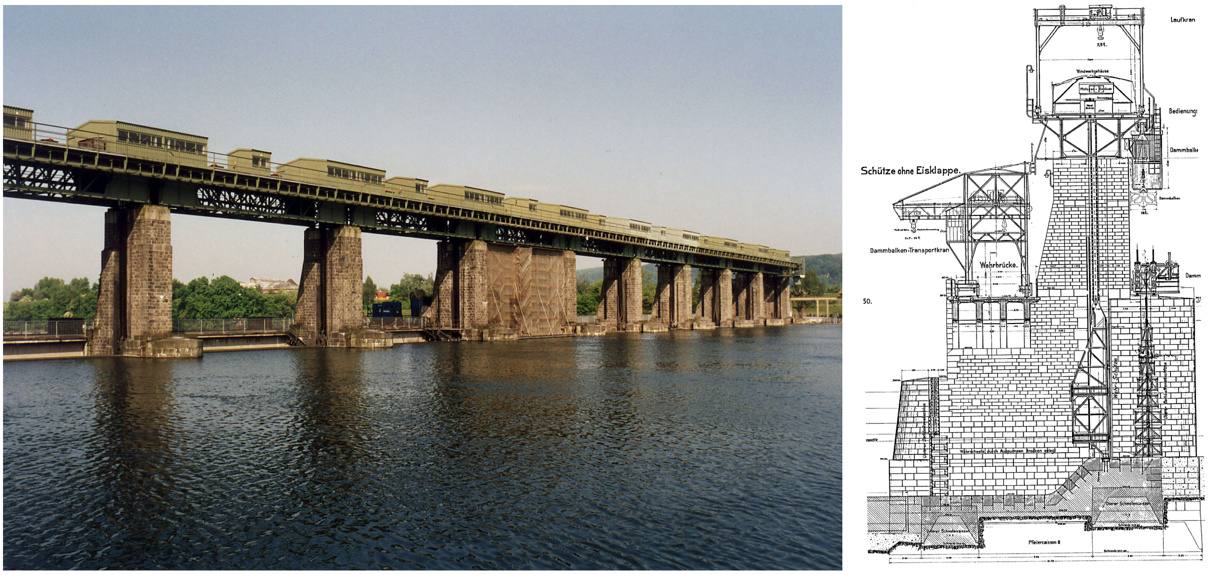

Fig. 10: Run-of-river power plant Augst-Wyhlen at Rhine River: weir with steel truss bridge for gate operation equipment (left) and details of a typical pier made of concrete and a surface protection made of stone masonry blocks (right)

9.6 Other Aspects: Strong Motion Instrumentation and Post-earthquake Inspections

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 based on the recorded site motion. This data allow the analysis of the behaviour of the dam during the recorded earthquake. 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 behaviour or have any safety defects.

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

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 type of intervention is set on the basis of the comparison between the accelerations measured at the site and the PGA of the SEE. For those dams that are not instrumented, the required inspection is defined based on the estimated earthquake motions at the dam site (estimated site intensity).

9.7 A Comparison of Earthquake Guidelines in Neighbouring Countries

A working group was set up by the Swiss Dam Society to compare the Swiss earthquake guidelines for the seismic safety evaluation of dams with those of the neighbouring countries. The guidelines of the following countries were considered: Austria, Italy, France, Germany and Switzerland (new regulations for design of buildings and bridges). Among these countries only Switzerland and Germany have modern guidelines, which have been approved recently. The new guidelines of the other countries are either available as draft (Italy and France) or are of rather general nature as in the case of Austria. The comparison of the Swiss guideline for dams with that for buildings and bridges (building code) has shown that there are certain cases (depending on location and dam type) where the application of the building code would be more rigorous. The Swiss guidelines for dams (BWG 2003) are at present considered to be at the forefront in Central Europe. As the development in earthquake engineering is still progressing relatively fast and since experience and observations on the earthquake behaviour of modern dams is very limited, it is necessary not only to look at the development at home or the region but also at what happens internationally.

It must also be emphasized that a prerequisite for favorable earthquake behaviour the dams have to be maintained properly, which is sometimes difficult for dams that are not used for power production and the dam owner has a limited or no maintenance budget. We have to realize that a single catastrophic failure of a dam will have a negative feed-back on the whole dam industry.

10. ICOLD'S ACTIVITIES IN SEISMIC SAFETY OF EXISTING DAMS

The seismic safety of existing dams has been a subject of ICOLD's Committee on Seismic Aspects of Dam Design since 1999. No specific guideline or bulletin has been drafted yet as this topic is still under development in most countries. Based on ICOLD's initiative and the different meetings of the earthquake committee, which has members from some 25 different countries, many member countries have taken up this matter and have started looking into the seismic safety of their dams. This can be considered as a big success.

Several countries like Japan, China, Russia, Canada, U.K., Switzerland, Germany, Australia, New Zealand, USA etc. have already new seismic design guidelines for dams, which may also be used for the assessment of existing dams.

It is interesting to note that quite a few countries with moderate to low seismicity have such guidelines. There is still some difference among the design criteria and the design concepts but compared to what has been used in the past a clear improvement can be noticed. If the PGA is used as a yardstick then the PGA values of the SEE varies from say 0.3 to 1.0 g depending on the seismic region. In some cases the SEE is considered as being a real earthquake rather than a design earthquake. If design earthquakes are developed mainly by seismologists, who know very little about the end user and the significance of the earthquake ground motion in the design of a dam, then sometimes too short durations of strong ground shaking and/or too low PGA-values are used. The duration of strong ground shaking of the SEE should be sufficient so it can also cover any effects due to fore- and aftershocks.

The ICOLD guidelines prepared for the seismic design of new dams shown below can also be used for the seismic safety assessment of existing dams. They represent the international state-of-the-practice and are used as a reference by most dam engineers.

1. Bulletin 52 (1986), Earthquake Analysis Procedures for Dams – State of the Art, ICOLD, Paris
2. Bulletin 72 (1989): Selecting Seismic Parameters for Large Dams, Guidelines, ICOLD, Paris
3. Bulletin 112 (1998): Neotectonics and dams, ICOLD, Paris
4. Bulletin 113 (1999): Seismic observation of dams, ICOLD, Paris
5. Bulletin 120 (2001): Design features of dams to effectively resist seismic ground motion, ICOLD, Paris
6. Bulletin 123 (2002): Earthquake design and evaluation of structures appurtenant to dams, ICOLD, Paris

It can be expected that in the coming years further progress can be achieved in the seismic safety evaluation of existing dams.

11. CONCLUSIONS

The technology for designing and building dams and appurtenant structures that can safely resist the effects of strong ground shaking is available. Dam construction has moved from the West to the less developed countries and the existing dams are ageing not only physically but also the design criteria and design concepts are getting old. This is particularly true for seismic action where a lot of developments have taken place since the 1971 San Fernando earthquake, a milestone in modern earthquake engineering.

Dams are not inherently safe against earthquakes. In regions of low to moderate seismicity where strong earthquakes occur very rarely, it is sometimes believed (i) that too much emphasis is put on the seismic hazard and earthquake safety of dams, and (ii) that dams designed for a seismic coefficient of 0.1 are sufficiently safe against earthquakes as none of them has failed up to now.

For the earthquake safety evaluation the same criteria (dam must withstand the MCE ground motion) as for the hydrological safety (PMF must be released safely) have to be considered. As most dams built prior to 1989 when ICOLD has published its seismic design criteria of dams, have not been checked for the behaviour and safety for the maximum credible ground motion at the dam site, the earthquake safety of these dams is not known and based on the comprehensive safety checks carried out in California it must be assumed that quite a number of them do not satisfy today's seismic safety criteria. Therefore, owners of older dams shall start with the seismic safety checks of their dams.

They shall also realize (i) that the earthquake load case has evolved as the critical load case for most large dams even in regions of low to moderate seismicity and (ii) that due to changes in the seismic design criteria and the design concepts it may be necessary to perform several seismic safety checks during the long economical life of a large dam. This is also true for other infrastructure projects and buildings.

Finally we have to realize that our knowledge on the behaviour of large dams during very strong ground shaking is still very limited and that each destructive earthquake affecting dams may reveal some new features, which up to now may have been ignored (Fig. 11).

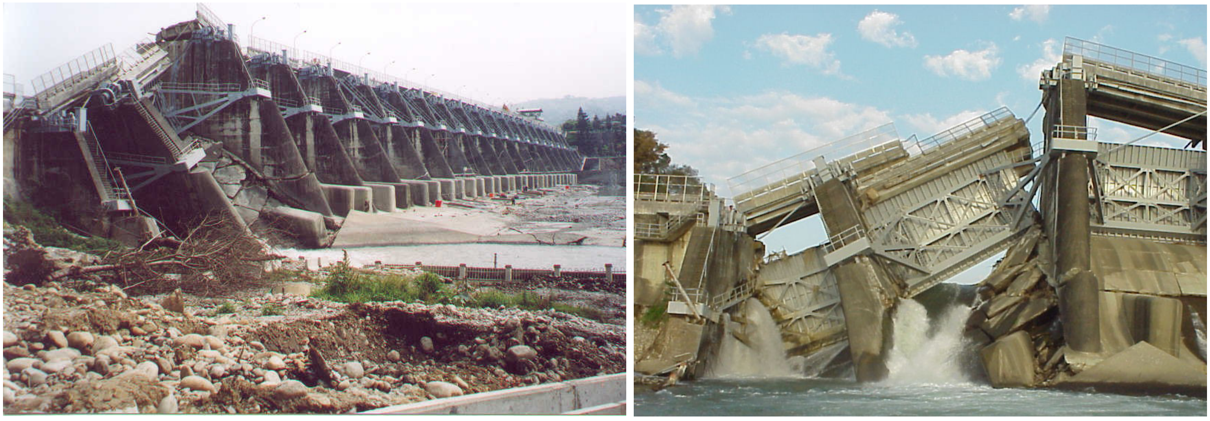

Fig. 11: Damage at Shih-Kang weir caused by movements along the Chelungpu fault during the 1999 Chi-Chi earthquake in Taiwan (relative vertical displacements of 7.7 m, reservoir was released by the two destroyed spillway openings)

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