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THE ACTIVITIES OF THE INTERNATIONAL COMMISSION ON LARGE DAMS (ICOLD) IN THE EARTHQUAKE SAFETY OF LARGE DAMS

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SUMMARY

The International Commission on Large Dams (ICOLD), founded in 1928, with 82 national committees and ca. 7000 members leads the profession in ensuring that dams are built safely, efficiently, economically, and without detrimental effects on the environment. The ICOLD publications represent the state-of-practice in dam engineering in many countries, including the earthquake safety of large dams. Large dams were among the first structures, which were designed against earthquakes and this subject was first discussed at the ICOLD congress in 1955 in Paris and most recently at the 21st congress in Montreal in 2003. Since 1975, ICOLD has published 10 bulletins on different aspects of earthquake safety of large dams. The activities of the ICOLD Committee on Seismic Aspects of Dam Design, which has representatives from different countries, are discussed.

INTRODUCTION

Large dams were among the first structures where seismic design criteria had been considered as early as the 1930s in the case of concrete dams (Hoover dam, pseudo-static inertia forces and hydrodynamic forces after Westergaard), and even earlier for embankment dams (pseudo-static slope stability analysis). Until the publication of ICOLD Bulletin 72 in 1989: *Selecting seismic parameters for large dams,* it was common practice to design dams against earthquakes using the pseudo-static approach, typically for a horizontal acceleration of 0.1 g. It is nowadays recognized that earthquakes could produce ground accelerations considerably higher than the values assumed at the time of the design of many existing dams. Furthermore, it is also recognized that large dams, while having the appearance of rigid bodies, do respond dynamically to earthquake ground motions.

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ICOLD is concerned with large dams, i.e. dams with a height of over 15 m. Some 45,000 dams fall under this category. The country with the largest number of large dams is China. There are very few recorded cases where a large well-designed dam has been severely damaged during a strong earthquake. This observation is made with the recognition that reporting of dam incidents in earthquakes may not be as complete as one would prefer. Since most of the existing dams have been designed by methods, which, today, are considered as outdated the earthquake safety of these dams is not known – some older dams may even be unsafe. ICOLD's committee on Seismic Aspects of Dam Design, which is chaired by the first author, has to look into these issues in a broader sense, although the terms of reference are much more specific as discussed in the following section.

The Special Theme Session on Seismic Aspects of Large Dams at the 13 WCEE shall serve as a forum for the exchange of experience among practitioners, and for the presentation of the state-of-the-practice on the subject.

ACTIVITIES OF ICOLD COMMITTEE ON SEISMIC ASPECTS OF DAM DESIGN

ICOLD Bulletins on Seismic Aspects of Dam Design

The Committee on Seismic Aspects of Dam Design has representatives (dam engineers, earthquake experts) from 26 different countries from Europe, North and South America, Africa, Asia and Australia, Since 1975 the following bulletins were published by ICOLD, which were mainly prepared by the seismic committee.

- Bulletin 27 (1975): A review of earthquake resistant design of dams
- Bulletin 46 (1983): Seismicity and dam design
- Bulletin 52 (1986): Earthquake analysis procedures for dams (Report prepared by O. C. Zienkiewicz, R. W. Clough, and H. B. Seed)
- Bulletin 62 (1988) : Inspection of dams following earthquakes - guidelines
- Bulletin 72 (1989): Selecting seismic parameters for large dams
- Bulletin 98 (1995): Tailings dams and seismicity – Review and recommendations
- Bulletin 112 (1998): Neotectonics and dams
- Bulletin 113 (1999): Seismic observation of dams
- Bulletin 120 (2001): Design features of dams to effectively resist seismic ground motion
- Bulletin 123 (2002): Earthquake design and evaluation of structures appurtenant to dams

In addition, seismic aspects are also addressed in a number of other ICOLD Bulletins.

Of these Bulletins, Bulletin 72 has had the largest impact in that it provided a clear concept of the seismic design criteria for dams and introduced the two-level design earthquake concept. It calls for checks of the seismic safety of dams for ground motions which are usually higher than those used in the past.

Bulletin 120 provides general qualitative guidelines to arrive at the design of a dam, which is very likely to perform well during strong earthquakes without having to perform sophisticated analyses in the preliminary design phase.

In Bulletin 112, the rather sensitive issue of dams located on potentially active faults is discussed. This is a subject, where hardly any technical papers can be found in the literature. Standard practice is to analyse the dynamic behaviour of dams due to ground shaking only.

In discussions with dam engineers and owners, it is often realized that they are not aware of or have no access to the ICOLD Bulletins or they cannot understand them due to language problems. Therefore, public awareness and access to this important source of information must be improved.

Terms of Reference and Current Activities

The terms of reference of the current Committee on Seismic Aspects of Dam Design are:

(i) Seismic safety of existing dams: A large number of the existing dams were designed according to analytical capabilities prevailing at the time the respective dams were built. More precise knowledge on the safety of existing dams (using up-to-date analyses) is increasingly considered a necessity. The focus will be on the reassessment of the seismic safety of existing dams.

(ii) Seismic interpretation of integrated observation data: The primary objective is to look into the existing strong motion data recorded at large dams. Modern automated observation of dams also furnishes response time histories of deformations and stresses in the dam body and its foundations under seismic loads. Integrated consideration of such results provides a fuller picture of dam response. The focus will be on the strong motion and response instrumentation of large dams.

(iii) Reservoir-triggered seismicity (RTS): An understanding of reservoir-triggered seismicity phenomena was reached during the 1970s. But observation data and general knowledge about the seismic response of dam impounding are accumulating. A general reassessment of the state of knowledge in this field is the objective.

(iv) Seismic risk determination and related techniques: One of the basic objectives in safety considerations is the determination of seismic risk for each particular dam. The focus will be on the seismic hazard assessment and the earthquake vulnerability of dams. The consequences of dam failures are the task of other technical committees and only the specifically seismic consequences are discussed.

Work on these four subjects is under way. The main subject – and a very difficult one - is the seismic safety of existing dams. Several countries are now addressing the seismic safety of the existing dams or have corresponding plans.

A global review of the state-of-practice in seismic aspects of dams was discussed during the 21st ICOLD Congress, which was held in Montreal in June 2003. The 73 papers received from 23 different countries and published in Volume 3 of the proceedings, covered the following relatively broad areas:

- Observed earthquake effects on dams and seismic hazard assessment
- Seismic aspects of embankment dams including liquefaction
- Seismic aspects of concrete dams
- Seismic rehabilitation of dams and appurtenant structures

OVERVIEW OF SEISMIC ASPECTS OF DAMS

Initially, the development in the earthquake safety of dams has been strongly influenced by the seismic design concepts and dynamic analysis tools developed for the nuclear industry in the late 1960s and 1970s. The 1971 San Fernando earthquake, which severely damaged the Lower San Fernando dam, a hydraulic fill dam, and caused large ground motions and minor damage at the Pacoima arch dam, had a major impact. Up to that time, dams were designed against earthquakes using the pseudo-static approach mentioned above.

The evaluation of the earthquake behaviour of dams is a challenging task, as it requires more sophisticated analysis tools than those used for the usual static loads. Significant progress has been achieved in the linear-elastic dynamic analysis of concrete dams and the equivalent linear method has been developed for embankment dams, which has been widely used for practical applications. The true nonlinear dynamic behaviour of concrete dams, taking into account contraction joint opening and cracking of mass concrete, and of embankment dams is still under research and development. Also dynamic concrete dam-foundation interaction is a problem, which has not yet been solved satisfactorily as the proposed foundation models are far from representing reality.

Significant progress has also been achieved in the understanding and in the testing of the dynamic characteristics of embankment and foundation materials.

Before substantial further progress is possible, additional information has to be collected from dams, which have experienced severe ground shaking similar to that expected during the Maximum Credible Earthquake (MCE). These events will reveal the true nature of earthquake problems of dams. In the absence of such information, it is necessary to perform model tests up to dam failure. In such tests, the main parameters have to be modelled accurately, i.e. contraction joints and lift joints in mass concrete, joints in foundation rock, and soil properties of embankment dams etc. For embankment dams, dynamic centrifuge model tests are promising, since they enable compliance with model similitude requirements and thus better represent the stresses and the inelastic behaviour of prototype dams. The characteristics of near-fault ground motions with high velocity pulses must also be considered.

In spite of the fact that the development of numerical analysis methods has progressed significantly, further information is needed before the behaviour of large dams during strong ground shaking can be determined accurately. The main issues are:

- Selection of characteristics of seismic ground motion for MCE and SEE (Safety Evaluation Earthquake);
- Determination of seismic failure modes of different types of dams;
- Modelling of materials and identification of dynamic material properties;
- Selection of damping properties of concrete dams during strong ground shaking;
- Modelling of dam-foundation-reservoir system and nonlinear dynamic analysis; and
- Definition of performance criteria for different types of dams.

The need to address most of the above issues has been known for a long time. It is also recognized that engineering judgment is often involved.

The seismic safety evaluations have to be performed with the tools that exist today and it is questionable wisdom to wait for tools that may become available sometime in the future. The dam owners are not keen to spend money on investigations and studies that may be outdated in 10 or 20 years and thus may have to be repeated in view of new developments. Unfortunately, this is the current situation. Seismic safety evaluations of dams have already been carried out in a few countries (Babbitt, 2003).

It has to be recognized that earthquakes affect 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, according to today's state-of-the-practice, 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 specifically into their respective problems.

For the safety-relevant components, the same seismic design criteria shall be used as for the dam. For the non-safety-relevant appurtenant structures, the seismic building codes may be used if no specific guidelines exist.

As the earthquake safety of many dams is unknown and new dams – mainly small ones – are being built by organisations whose experience in dam construction may not be adequate, it is important to reach the people responsible for those projects so that a uniform (risk-based) safety standard can be achieved in the future.

SEISMIC SAFETY ASPECTS AND SEISMIC PERFORMANCE CRITERIA

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

(i) Structural Safety: site selection; optimum dam type and shape; construction materials and quality of construction; stiffness to control static and dynamic deformations; 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; plastic deformation characteristics of embankment materials); stability (sliding and overturning stability), etc.

(ii) Safety Monitoring and Proper Maintenance: strong motion instrumentation of dam and foundation; visual observations and inspection after an earthquake; data analysis and interpretation; post-earthquake safety assessment etc. Dams should be maintained properly including periodic inspections.

(iii) Operational Safety: Rule curves and operational guidelines for post-earthquake phase; experienced and qualified dam maintenance staff, etc.

(iv) 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.

These basic safety elements are almost independent of the type of hazard.

For the seismic design of dams, abutments and safety relevant components (spillway gates, low level outlets, etc.) the following types of design earthquakes are used (ICOLD Bulletin 72):

(i) 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 easily repairable damage is accepted.

(ii) 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. In practice, due to the difficulties involved in estimating MCE ground motions, the design earthquake is usually determined probabilistically with a typical return period of 10,000 years for countries of low to moderate seismicity. 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 event 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. The performance criteria for dams during the OBE and MDE/SEE are of very general nature and have to be considered on a case-by-case basis.

EARTHQUAKE DAMAGE OF DAMS

The 21 June, 1990 Manjil-Rudbar earthquake (magnitude 7.7) was one of the most devastating seismic events in the Caspian Sea region. It resulted in the loss of over 35,000 lives and the total destruction of the town of Manjil and caused damage to the Sefid Rud dam, a buttress type gravity dam with a maximum height of 106 m and a crest length of 417 m. There are 23 buttresses, 14 m wide, with a web thickness of 5 m, and two gravity type abutment blocks. The dam stores a reservoir volume of 1.8 billion m^3. The right hand side of the dam is founded on competent andesite rock while the left part rests on andesite breccia and pyroclastic rock. Construction of the dam took place from 1958 to 1962. Damage to the dam structure consisted mainly of cracks along horizontal working joints and of spalling of concrete along the vertical joints between buttress heads (Fig. 1; Wieland et al., 2003). These damage features mainly affected the central buttresses and they were concentrated predominantly at the level of the change in the slope of the downstream face. There was at least one major horizontal crack along working joints in most of the buttresses. These working joints were spaced at 2 m.

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

The Shih-Kang weir, located at the Da-Jia river in Taiwan, comprises two sluiceways and 18 spillway gates. On September 21, 1999, the concrete weir was severely damaged during the magnitude 7.3 Chi-Chi earthquake and the reservoir with a volume of 2.7 million m^3 was released through the two destroyed spillway gates. The most spectacular damage occurred at spillways 16 to 18 near the right abutment and was due to fault movements (reverse faulting) of several metres mainly in the vertical direction (Fig. 2). From this observation, it can be concluded that concrete dams cannot be designed economically to resist fault movements of the magnitude observed at the Shih-Kang weir.

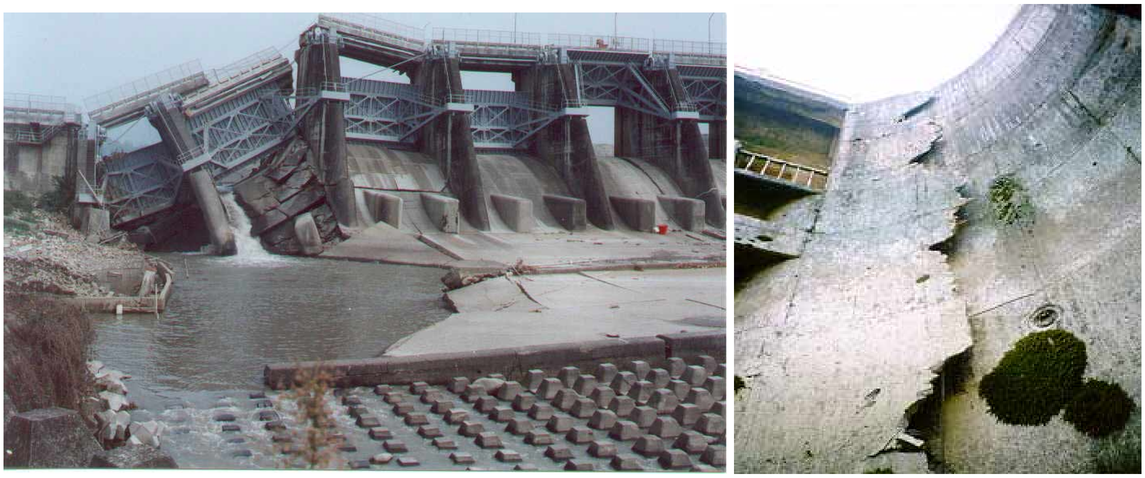

Fig. 2: Two bays of the Shih-Kang weir destroyed by fault movements during the 1999 Chi-Chi earthquake in Taiwan (left) and fault passing through intake structure (right)

The Bhuj Earthquake with a magnitude 7.7 occurred on January 26, 2001. The epicenter was located about 65 km East of Bhuj town in Kachchh district, Gujarat State, India. 245 earthen dams, most of them with a height of less than 15 m and built on soil, were damaged and needed quick repair before the monsoon season. As the water levels in all the reservoirs were very low, no catastrophic release of reservoir storage occurred. The main features of the damage were deformations and cracks due to liquefaction and slope movements (Fig. 3). Most of the dams in the region were constructed in the 1950s and 1960s without considering seismic effects in the design.

Fig. 3: Deformations in embankment dams caused by 001 Bhuj earthquake in India

EARTHQUAKE SAFETY OF EXISTING DAMS

The seismic safety of the 1200 dams that are under state supervision in California and the 175 dams, which are owned by the federal government, was evaluated in a comprehensive dam safety program (Babbitt, 2003). About 10% of the dams had an earthquake safety problem. The information on 116 California dams, that have had their seismic safety improved, is summarized in Table 1. Both structural and non-structural improvements were necessary.

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

Table 1: Seismic improvements to 116 dams in California, Babbitt (2003), (Note: Several dams have more than one type of improvement)

In Fig. 4 the safety improvement of the spillway structure of the Whakamura gravity dam in New Zealand is shown. The problem was mainly due to an underestimate of the seismic hazard and the neglect of the amplification of the ground shaking from the base to the crest. It must be pointed out that seismic rehabilitation is mainly needed when either the seismic hazard has been underestimated and/or the dynamic characteristics of the structure, the construction materials or the foundation have not been considered or incorrectly assessed.

Fig. 4: Strengthening of of crest spillway of the 56 m high Whakamura gravity dam in New Zealand (left: original design of 1956 with seismic coefficient of 0.1; right: strengthened structure with design acceleration of 1.9 g); Foster and Black (2003)

RESERVOIR-TRIGGERED SEISMICITY

If a large dam has been designed according to the current state-of-practice, which requires that the dam can safely withstand the ground motions caused by the MCE, it should also be able to withstand the effects of the largest reservoir-triggered earthquake, as the maximum reservoir-triggered earthquake cannot be stronger than the MCE. Thus, reservoir-triggered seismicity (RTS) is not a safety problem for a well designed dam or the people who could be at risk in the case of a dam failure. However, RTS may still be a problem for the buildings and structures in the vicinity of the dam, because they tend to have a much lower earthquake resistance than the dam.

In the great majority of RTS, the magnitudes are small. However, reservoir-triggered earthquakes often have a shallow focus and their epicentres are relatively close to the dam sites or the reservoir, causing PGA values that can be quite high for the strongest events.

RTS is also a subject which is brought forward by dam opponents. Although RTS is usually not a dam safety problem, it is recommended to install a seismic network in the reservoir region of large dams, where RTS is expected. This will also help address any public concerns competently.

SEISMIC TOPICS REQUIRING FURTHER ATTENTION

As the field of earthquake safety of dams is still relatively young, new lessons are learnt from each strong earthquake, which either causes damage to a large dam, or provides strong motion and response records of instrumented dams. As very few large concrete dams have been damaged during an earthquake and since the few dynamic model tests carried out with dam models up to rupture are not really representative, there are still considerable uncertainties about the behaviour of a dam under very strong ground shaking. The following topics need further attention:

- inelastic earthquake behaviour of concrete and embankment dams under strong ground shaking;
- dam design methods for MDE/SEE including development of simplified methods for the assessment of the dynamic stability of cracked concrete dams and the dynamic slope stability of embankment dams;
- methods for seismic strengthening of existing dams;
- seismic hazard assessment and refinement of seismic dam design criteria including estimation of strong ground motions at specific dam site from specific causative faults; and seismological investigation of new tectonic faults);
- seismic safety of concrete-face rockfill (CFR) and roller compacted concrete (RCC) dams;
- dynamic strength properties of concrete gravity, RCC and CFR dam materials (dynamic tensile strength of mass concrete, tensile strength in lift joints and contraction joints, etc.);
- analysis of effect of fault movements in dam foundations on behaviour and safety of existing dams;
- seismic design of underground structures (tunnels, caverns, shafts);
- seismic design of hydromechanical equipment (gates, penstock, valves, bottom outlets, intake structures, etc.);
- dynamic slope stability in reservoir area;
- foundation and abutment stability of arch dams during earthquakes, etc.

CONCLUSIONS

The technology for building dams and appurtenant structures that can safely resist the effects of strong ground shaking is available. New concepts are still needed for very high dams in highly seismic regions, for dams at difficult sites, and new types of dams such as roller compacted concrete and concrete-face rockfill dams (Wieland and Brenner, 2004).

In regions of low to moderate seismicity where strong earthquakes occur very rarely, it is sometimes believed (a) that too much emphasis is put on the seismic risk and earthquake safety of dams, and (b) that dams designed for a seismic coefficient of 0.1 using the outdated pseudo-static design method are sufficiently safe against earthquakes. These beliefs are not tenable. The times when earthquakes were considered as an acceptable risk and thus have been ignored in design have long passed. It must also be recognized that the pseudostatic design concept based on a seismic coefficient is outdated and in many cases even wrong.

For the earthquake hazard the same criteria as for the flood hazard have to be considered. A reasonably conservative seismic design is still the best insurance for a safe, long life of a dam.

Some of the main issues to be resolved in future are as follows:

- reassessment of the seismic safety of the existing dams and rehabilitation of the dams with unacceptable seismic risk;
- earthquake safety of small dams that have not been designed by engineers; and
- consistent use of risk-based seismic design criteria for new dams.

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