LARGE DAMS THE FIRST STRUCTURES DESIGNED SYSTEMATICALLY AGAINST EARTHQUAKES

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ABSTRACT

Large dams were among the first structures for which seismic design had been performed. The seismic analysis method developed by Westergaard in the 1930s has found worldwide acceptance among dam designers until the late 1970s. This relatively simple pseudostatic analysis method accounts for both the inertial effects of the dam and the hydrodynamic pressure. It was common practice to use a seismic coefficient of 0.1 if no information on the seismic hazard was available. It is nowadays recognized that earthquakes can produce ground accelerations considerably higher than the values assumed at the time of the design of many existing dams. The effect of earthquakes on the design of dams was first discussed at thee 5th Congress of the International Commission on Large Dams (ICOLD) in 1955. Since then the ICOLD Committee on Seismic Aspects of Dam Design, which at present comprises dam and earthquake experts from 28 different countries, has prepared a number of guidelines on various aspects of seismic analysis, design and seismic monitoring of dams. These guidelines are de facto considered as seismic codes in countries which do not have any specific codes or regulations for dams. The ongoing work of ICOLD's Committee on Seismic Aspects of Dam Design is discussed. Moreover, aspects which need closer attention in the future are discussed such as good practice in dam engineering and the integral safety of dams, which includes structural safety, dam safety monitoring, operational safety and dam maintenance, and emergency planning.

KEYWORDS: Concrete dam, seismic analysis of dams, seismic design, dam safety

1. INTRODUCTION TO SPECIAL SESSION ON SEISMIC ASPECTS OF LARGE EMBANKMENT AND CONRETE DAMS

1.1. General

Dams are important structures, which have contributed significantly to the economic development of many countries. The great majority of existing dams – mainly smaller ones - were built for irrigation and water supply. Most large dam projects are multipurpose projects for energy production, flood control, navigation, water supply and irrigation, recreation, aquaculture etc. As large storage dams may have very large damage potentials, they must also be able to withstand the effects of very strong earthquakes.

In several Western countries dams were built wherever feasible and very few new dams are now being constructed. For example, the average age of the existing dams in Switzerland is about 50 years. Therefore, the interest in the earthquake safety of dams has to some extent stagnated. In many developing countries there is still a large potential for technically and economically feasible dam projects, but these dams may be located in less favorable locations than those already developed. One of the important factors is the high seismic hazard of some of these sites. Therefore, the earthquake load case has become the dominant one for the design of some of the new large dams. This was not the case when most of the existing dams were built, because the seismic design criteria (low seismic coefficient) and methods of dynamic analysis (pseudostatic analysis) used at that time were such that the earthquake safety of the dam was automatically satisfied and hardly any special seismic design modifications were needed. In the meantime the seismic design criteria and methods of dynamic analysis have changed dramatically and because of these changes there is also an increasing demand for checking the earthquake safety of the existing dams designed against earthquakes using design criteria and methods of analysis, which are considered as outdated and sometimes wrong, today.

To increase the awareness of the dam designers and the parties involved in dam safety and also to motivate further research and development in earthquake-safe and resilient dams, special theme sessions were organised

with the support of the earthquake committee of the International Commission on Large Dams (ICOLD) at the following World Conferences on Earthquake Engineering: Acapulco (1996), Auckland (2000), Vancouver (2004) and in Beijing (2008). In Beijing (14WCEE) the Special Session on Seismic Aspects of Large Embankment and Concrete Dams was organised by Chen Houqun of IWHR, China and the author of this paper. A brief description of this special session is given in Section 1.2.
Similar sessions were also organised at the European Conferences on Earthquake Engineering in Vienna (1994) Paris (1998), London (2002) and Geneva (2006). Various aspects of seismic safety of dams were discussed in these conferences. Therefore, in the related proceedings many useful papers on this subject can be found.
The present paper is intended to be the introductory paper for this Special Session at the 14 WCEE in Beijing. This session is also a very timely one in view of the fact that a large number of dams has been affected by the May 12, 2008 Wenchuan earthquake in Sichuan province.
In the subsequent sections a short overview on past seismic analysis and design procedures for dams, the work of ICOLD in the field of seismic safety of dams, the integral safety philosophy for dams, where earthquake safety plays a central role, and future research needs are briefly discussed.
The importance of earthquakes for large dams is best illustrated by Fig. 1. The world's largest dam, Usoy dam, with a maximum height of ca. 650 m is a landslide dam in Tajikistan formed by a magnitude 7.3 earthquake in 1911. The landslide (dam) volume is over 2 billion m^3 and the reservoir stored behind this dam, Lake Sarez, has a volume of 17 billion m^3 and a maximum water depth of some 600 m. Also in Fig. 1 a modern arch dam is shown where a fault is crossing the dam at the left abutment. The dam is located close to a major fault passing through the reservoir.

Fig. 1: Usoy dam in Tajikistan created by landslide triggered by magnitude 7.3 earthquake in 1911 (left) and arch dam in Iran with fault crossing the left abutment (right)

1.2. Brief Description of Special Session and Needs for further Research and Development

The Special Session on 'Seismic Aspects of Large Embankment and Concrete Dams' will be organized in cooperation with the Committee on Seismic Aspects of Dam Design of ICOLD.
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 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 the maximum credible earthquake (MCE) or safety evaluation earthquake (SEE). It may be expected that in the coming years further developments are made, e.g., in the following fields:

- inelastic earthquake behaviour of dams under strong ground shaking of MCE/SEE;
- dam design to resist MCE/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;
- efficient seismic strengthening of existing dams;

- seismic hazard assessment and refinement of seismic dam design criteria;
- short-term behaviour of mass concrete, RCC and embankment dam materials (dynamic tensile strength of mass concrete, tensile strength in lift joints and contraction joints);
- simulation of effect of fault movements in dam foundations on behaviour and safety of dams;
- seismic safety of concrete face rockfill (CFR) dams and roller compacted concrete (RCC) dams;
- seismic design and safety of underground structures (tunnels, caverns, shafts);
- hydromechanical equipment (gates, penstock, valves, bottom outlets, intake structures etc.)
- dynamic rock slope stability in reservoir area, triggering of landslides and rockslides (mass movements) in reservoir area;
- foundation stability of dams during earthquakes, etc.

Therefore, contributions on the following subjects are invited for presentation and discussion:

- Seismic safety of existing dams;
- Effects of recent earthquakes on dams and strong motion data;
- Reservoir-triggered seismicity;
- Seismic hazard assessment at dam sites;
- Seismic design criteria for large dams;
- Faults in dam foundations;
- Seismic aspects of underground works;
- Seismic aspects of slope stability of embankment dams and slope stability in reservoir region;
- Seismic aspects of roller compacted concrete and concrete-faced rockfill dams; and
- Seismic aspects of diaphragm walls and grout curtains in dam foundations.

2. SEISMIC ANALYSIS OF CONCRETE AND EMBANKMENT DAMS

2.1. Concrete dams

Large concrete dams were among the first structures for which seismic analysis and design had been performed. The seismic analysis method that was originally developed by Westergaard in the 1930s for the Hoover dam has found worldwide acceptance among designers of concrete dams until the late 1970s. This relatively simple pseudostatic analysis method accounts for both the inertial effects of the dam and the hydrodynamic pressure. It was common practice to use a seismic coefficient of 0.1 if no information on the seismic hazard was available. It is nowadays recognized that earthquakes can 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 concrete dams respond dynamically to earthquake ground motions and that peak values of the acceleration can be amplified by up to a factor of 10 from the base to the crest of arch dams.

2.2 Fill dams

The first dynamic response analysis of an earth dam was made by Mononobe et al. already in 1936. They modeled the dam as an infinitely long symmetrical triangular section consisting of linear-elastic material and resting on a rigid foundation (Mononobe et al., 1936). However, general design practice at that time was to take account of the seismic loading of a dam by a seismic coefficient. This seismic coefficient was commonly between 0.10 and 015. The concept was that the seismic forces acting on the dam could be represented by a static horizontal force expressed as the product of the seismic coefficient and the weight of the potential sliding mass in the dam body. If in a static stability analysis the factor of safety would approach unity, the dam would be considered close to failure and therefore unsafe.

Earth dam design prior to the 1960s was mainly empirical using judgment guided by past experience. At those times, sites for dams were generally unproblematic and engineers were confident that they could build completely safe structures. Little attention was given to the consequences of a possible failure. The confidence in the ability to build safe dams was derived from the satisfactory performance of a large number of existing dams. However, there was a severe lack of precedence of dams which had been subjected to strong shaking by an earthquake. Moreover, there were practically no quantitative data on the response of concrete and earth dams to strong ground motions due to the absence of instrumentation.

There is no relationship between the peak ground acceleration (PGA) and the seismic coefficient in an analysis. Marcuson (1981) suggested that appropriate pseudostatic coefficients for dams should correspond to one-third to one-half of the PGA. Hence, pseudostatic analysis, because of its simplicity, may still have some merits today, at least for preliminary design. However, as soon as the materials in the dam or in its foundation show a tendency to build up significant pore water pressures, or lose more than about 15 % of their strength during seismic loading in a laboratory test, the use of seismic coefficients is unsafe and must be strictly abandoned.
For embankment dams, the design practice was similar to that of concrete dams, but great efforts were made in understanding the dynamic behaviour of these dams after several failures had occurred due to liquefaction during major earthquakes in the 1960s and especially after the 1971 San Fernando earthquake in California.

3. THE ROLE OF THE INTERNATIONAL COMMISSION ON LARGE DAMS (ICOLD) IN THE EARTHQUAKE SAFETY OF LARGE DAMS

During the magnitude 8 Wenchuan earthquake, which occurred on May 12, 2008 in Sichuan province, China, some 1580 dams were affected by the earthquake and suffered different types of damage. Most of these dams were small dams, but also some large dams were damaged. Many large dam projects are currently under construction or in the design phase in Sichuan, the province with one of the highest hydropower potential in China. Some 245 earthen dams – mainly small dams for water supply and irrigation - were damaged by the magnitude 7.7 Bhuj earthquake of January 26, 2001 in Gujarat, India. No failure occurred because all the reservoirs were almost empty at the time of the earthquake. Dams were also affected by the Kocaeli earthquake of August 17, 1999 in Turkey and during the September 21, 1999 Chi-Chi earthquake in Taiwan. These recent events have shown that the earthquake hazard continues to be a serious threat to dams. Therefore, ICOLD is closely following seismic safety problems related to dams.
The Committee on Seismic Aspects of Dam Design is one of ICOLD's oldest technical committees, which at present comprises dam and earthquake experts from 29 different countries from all continents. It has prepared a number of guidelines on various aspects of seismic analysis, design and seismic monitoring of dams. These guidelines are considered as seismic guidelines in most countries which do not have any specific codes or regulations for dams. Since 1984 the following guidelines have been prepared:

- Bulletin 52 (1986): Earthquake analysis procedures for dams (Report prepared on behalf of the Committee on analysis and design of dams of ICOLD, O. C. Zienkiewicz, R. W. Clough, H. B. Seed),
- Bulletin 62 (1988) : Inspection of dams following earthquakes – guidelines (revised in 2008),
- Bulletin 72 (1989): Selecting seismic parameters for large dams (currently under revision),
- 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, and
- Bulletin (2008): Reservoirs and seismicity: state of knowledge (in print).

The last bulletin is concerned with reservoir-triggered seismicity (RTS). The construction of large storage dams has become a controversial subject and one of the arguments against dams is RTS, which is catching the public imagination quickly.
The publication with the greatest impact on the seismic design of dams is Bulletin 72, which is currently under revision. In this guideline the concept of two earthquake level for the seismic design of dams was introduced internationally, i.e. the Operating Basis Earthquake (OBE) and the Maximum Credible Earthquake (MCE) ground motions. Today, most dams are designed against earthquakes using this concept, which can be considered as the minimum seismic design requirement for dams.
Bulletin 120 complements Bulletin 72 as it includes conceptual features for the seismic design of dams, which are extremely important as it is well-known that it will be difficult to have a structure to perform well during an earthquake when the basic seismic design concepts are not observed.
Besides bulletins, ICOLD is also organising congresses, which are held every three years. In each congress four technical questions are discussed.
Previous questions dealing with seismic aspects of dams, discussed at some of the congresses, were as follows:

- Settlement of earth dams due to compressibility of the dam materials or of the foundation, effect of earthquakes on the design of dams (Paris, France in 1955);
- Results and interpretation of measurements made on large dams of all types, including earthquake observations (Edinburgh, United Kingdom in 1964);
- Dams in earthquake zones or other unfavourable situations (Istanbul, Turkey in 1967);
- Seismicity and aseismic design of dams (New Delhi, India in 1979); and
- Seismic aspects of dams (Montreal, Canada in 2003).

Several other Questions discussed at ICOLD Congresses have also dealt with earthquake hazard and the seismic vulnerability of dams.
In November 2008 ICOLD will celebrate its 80th anniversary. 88 countries are members of ICOLD, which is one of the first international professional organisations in the world. Further details about this important organisation can be found under www.icold-cigb.net.

4. SEISMIC ANALYSIS AND DESIGN ASPECTS OF LARGE DAMS

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 the one expected during the maximum credible earthquake. Under such earthquake motion damage is expected to occur in most dams (Fig. 2).

Fig. 2: Damage in top portion of the 105 m high Sefid Rud buttress dam caused by the magnitude 7.5 Manjil earthquake in Iran in 1990 (left), damage in concrete face of Zipingpu concrete face rockfill dam caused by the magnitude 8 Wenchuan earthquake in China in 2008

In view of the large number of dams affected by the May 12, 2008 Wenchuan earthquake, it is expected that important lessons can be learnt from this powerful earthquake. These events will reveal the actual 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 can 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 problems are:

- Selection of characteristics of seismic ground motion for the safety evaluation earthquake (SEE);
- 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.

Most of the above problems need engineering judgment.

5. SEISMIC HAZARD AND SEISMIC DESIGN CRITERIA FOR LARGE DAM PROJECTS

5.1. Seismic Hazard

Earthquakes are multiple hazards, which have the following features in the case of a storage dam (Wieland, 2003):

- ground shaking causing vibrations in dams, appurtenant structures and equipment;
- fault movements in the dam foundation causing structural distortions;
- fault displacement in the reservoir bottom causing water waves or loss of freeboard; and
- mass movements into the reservoir causing impulse waves in the reservoir.

Other effects such as water waves and reservoir oscillations caused by ground shaking are of lesser importance for the earthquake safety of a dam. Usually the main hazard, which is addressed in codes and regulations, is the earthquake ground shaking. It causes stresses, deformations, cracking, sliding, overturning, liquefaction etc. In the subsequent parts the design criteria specified are for ground shaking only.
A hazard, which is often underestimated, is the large number of rockfalls in mountainous regions. These mass movements can block access to dam sites and the reservoir or may sometimes form landslide dams. During the Wenchuan earthquake of May 12, 2008 large landslides dammed rivers and formed over 33 lakes. Because of the mass movements and closed roads, some of the dams such as the 132 m high Shapai RCC arch dam, could not be reached and inspected for several weeks.
If a major earthquake occurs, which can cause damage to a well constructed dam that can withstand the SEE, then it has to be expected that the buildings and infrastructure in the dam and reservoir regions are severely damaged and that access to the dam site and the reservoir may be obstructed due to landslides, rockfalls, debris on roads, cracks in road surface, soil deformations, damaged bridges, local flooding etc. Access to remote dam sites may only be possible by helicopter.
Rapid response is a prerequisite for saving lives and this includes immediate access to the dam site for immediate safety and damage assessment. Access is gaining importance as an increasing number of dams, especially in remote areas or locations with difficult access during certain periods of the year, are monitored and operated by remote control centres. The severity of damage cannot be assessed easily by the available monitoring instruments. These are important factors in the case of emergency planning (ICOLD, 1988/2008).

5.2. Seismic Design Criteria for Dam and Safety-relevant Components

For the seismic design of dams, abutments and safety-relevant components (spillway gates, bottom outlets, etc.) the following types of design earthquakes are used in accordance with ICOLD Bulletin 72 (1989):

(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. 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 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 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. 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.
Because bottom outlets and spillway gates have to be operable after the SEE ground motion, the performance criteria for these safety-relevant elements are stricter than for the dam body, which may be cracked or has undergone different types of deformations.

6. SAFETY PHILOSOPHY FOR LARGE DAM PROJECTS

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), design of dam according to state-of-practice, 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.
It is obvious from the above list that structural safety and earthquake resistant design of a dam is only one element, but a very important one, in the overall safety philosophy of large dams.

7. 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. Such arguments are not correct.
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 (Wieland and Brenner, 2008).

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