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An Overview of Seismic Design Criteria for Large Dams

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***Abstract*— This paper discusses the seismic design criteria for concrete dams, methods of dynamic analysis for strong ground shaking, and provides information on possible anti-seismic design features for large dams. The effects of recent earthquakes on dams are studied and the observed historical earthquake behavior of large embankment and concrete dams are presented. The guidelines published recently by the Committee on Seismic Aspects of Dam Design of the International Commission on Large Dams (ICOLD) are presented, and the terms of reference of the Committee are discussed, the current activities of the committee in the field of earthquake safety of dams are discussed. A list of subjects on dams and earthquakes, which need further attention in the future, is provided. The importance of earthquake safety of large dams is presented in the general context of dam safety. Furthermore, the need for safe rural dams and strong motion instrumentation of large dams is emphasized. Unlike other actions from the natural and man-made environment, which dams have to resist, earthquakes pose probably the greatest challenge to dam engineers as earthquake ground shaking affects both the dams and appurtenant structures.**

***Keywords*— gravity dams, earthquake, seismic design, seismicity,**

I. INTRODUCTION

Since the 1971 San Fernando earthquake in California, major progress has been achieved in the understanding of earthquake action on concrete dams. The progress was mainly due to the development of computer programs for the dynamic analysis of dams. However, it is still not possible to reliably predict the behavior of dams during very strong ground shaking due to the difficulty in modeling joint opening and the crack formation in the dam body, the nonlinear behaviour of the foundation, the insufficient information on the spatial variation of ground motion in arch dams and other factors. The same applies to embankment dams where the results of inelastic dynamic analyses performed by different computer programs tend to differ even more than in the case of concrete dams. Also, considerable progress has been made in the definition of seismic input, which is one of the main uncertainties in the seismic design and seismic safety evaluation of dams.

It has been recognized that during strong earthquakes such as the maximum credible earthquake (MCE), the maximum design earthquake (MDE) or the safety evaluation earthquake (SEE) ground motions can occur, which exceed those used for the design of large dams in the past. Already a moderate shallow-focus earthquake with a magnitude of say 5.5 to 6 can cause peak ground accelerations (PGA) of 0.5 g. However, the duration of strong ground shaking of such events is quite short and the predominant frequencies of the acceleration time history are also rather high. Therefore, smaller concrete dams may be more vulnerable to such actions than high dams, which have predominant Eigen frequencies that are smaller than those of such ground acceleration records. We have to recognize that most of the existing dams have been designed against earthquake actions using the pseudo static approach with an acceleration of 0.1 g. In regions of high seismicity like Iran the PGA of the SEE may exceed 0.5 g at many dam sites. Therefore, some damage may have to be expected in concrete dams designed by a pseudostatic method with a seismic coefficient of 0.1. Because of the large differences between the design acceleration and the PGA, and because of the uncertainties in estimating the ground motion of very strong earthquakes at a dam site, mechanisms are needed that ensure that a dam will not fail if the design acceleration is exceeded substantially? In the case of large dams, ICOLD recommends to use the MCE as the basis for the dam safety checks and dam design. Theoretically no ground motion should occur, which exceeds that of the MCE. However, in view of the difficulties in estimating the ground motion at a dam site, it is still possible that larger ground motions may occur. Some 50 years ago, many structural engineers considered a value of ca. 0.2 g as the upper bound of the PGA, but today with more earthquake records available, the upper bound has exceeded 1 g and some important structures have already been checked against such high ground accelerations.

II. RECENT EARTHQUAKES AND DAMS

The following recent earthquakes have had some impact on dams:

(i) October 6, 2000, Western Tottori earthquake, Japan, M = 6.6:
Kasho gravity dam, undamaged under PGA of 0.53 g and peak crest acceleration of 2.1g; PGA in epicentral region > 0.5 g.

(ii) January 26, 2001 Bhuj earthquake, Gujarat, India, Richter magnitude: M = ca. 7.9 *(Fig. 1)*: □ca. 200 dams (mainly earth dams) with a height of less than 30 m need upgrading; ca. 18 large irrigation dams were severely damaged mainly due to liquefaction; □the reservoirs were almost empty at time of the earthquake preventing complete failure of the severely damaged dams; no strong motion data available.

(iii) March 24, 2001 Hiroshima earthquake, Japan, M = 6.8: □cracks and settlements in 184 earth structures; □peak ground acceleration (PGA) in epicenter region > 0.5 g.

(iv) June 23, 2001, South Peru earthquake, Peru, M = 8.4 deformations, cracks and liquefaction in tailings dams and tailings.

III. OBSERVED EARTHQUAKE PERFORMANCE OF LARGE DAMS

The historical earthquake behaviour of large dams can be summarized as follows:

(i) Largest dam: The world's largest dam, Usoi dam, with a maximum height of ca. 650 m is a landslide dam formed during a strong earthquake in 1911. The landslide (dam) volume is over 2 billion m3 and the reservoir stored behind this dam, Lake Sarez, has a volume of 17 billion m3 and a maximum water depth of some 600 m *(Fig. 2)*.

(ii) Reservoir-triggered seismicity: Koyna dam in India, a 102 m high straight gravity dam, and Hsinfengkiang dam in China, a 104 m high buttress dam, were shaken as the result of nearby earthquakes of Magnitudes 6.5 (1967) and 6.1 (1962), respectively. Both events were suspected of being caused by reservoir-triggered seismicity. Both dams developed substantial longitudinal cracking near the top. Damage was attributed to design or construction details that would be avoided in modern structures. The two dams were repaired and strengthened and are still in service.

(iii) Largest recorded accelerations: The 113 m high Pacoima arch dam in California was exposed to very strong ground shaking during the 1971 San Fernando and the 1994 Northridge earthquakes. In 1971 the peak acceleration measured on a ridge above the dam crest was 1.2 g and in 1994 peak accelerations at the crest exceeded 2 g. The dam suffered only minor damage, but the reservoir was not full during both earthquakes.

(iv) Embankment dam failure due to liquefaction: The 38 m high Lower Van Norman Dam, a hydraulic fill dam, experienced widespread liquefaction and major slope failures.
Overtopping of the crest and flooding of an area involving over 70,000 downstream residents was avoided because the reservoir water level was relatively low for the season when the earthquake occurred *(Fig. 3)*.

(v) Concrete dam: The 106 m high Sefid Rud buttress dam was severely damaged by theMagnitude 7.5 Manjil earthquake in the northwestern part of Iran. The epicenter was assumed to be less than one kilometer away from the dam site. This dam has probably been exposed to the strongest earthquake ground shaking of any concrete dam and the observed damage may be representative for the damage to be expected in gravity dams under the effect of the maximum credible earthquake. The dam was repaired and is still in service *(Fig. 4)*.

(vi) Concrete dams subjected to fault movements: The Shih-Kang weir in Taiwan was severely damaged by faulting during the 1999 Chi-Chi earthquake *(Fig. 5)*. The complete reservoir was released but did not cause serious flooding. Moreover, Inguri arch dam in Georgia, which with 271 m is the world's highest arch dam, is located on a potentially active fault [5].

Fig. 1: Cracks in downstream (left) and upstream faces (right) of two damaged embankment dams, 2001 Bhuj earthquake (Courtesy Prof. S. K. Jain)

Fig. 2: Usoi landslide dam and Lake Sarez formed by 1911 earthquake in Tajikistan (dam height ca. 650 m; freeboard ca. 50 m; dam volume ca. 2 billion m^3, world's largest dam) (Courtesy J. Hanisch)

Fig. 3: Lower Van Norman Dam, a 38 m high hydraulic fill dam, experienced widespread liquefaction and major slope failures during the 1971 San Fernando earthquake, California (Courtesy Steinbrugge Collection, Earthquake Engineering Research Center, University of California, Berkeley)

Fig. 5: Local damage of Shih-Kang weir due to large fault movement near right abutment, 1999 Chi-Chi earthquake, Taiwan (Courtesy C. K. Yeh)

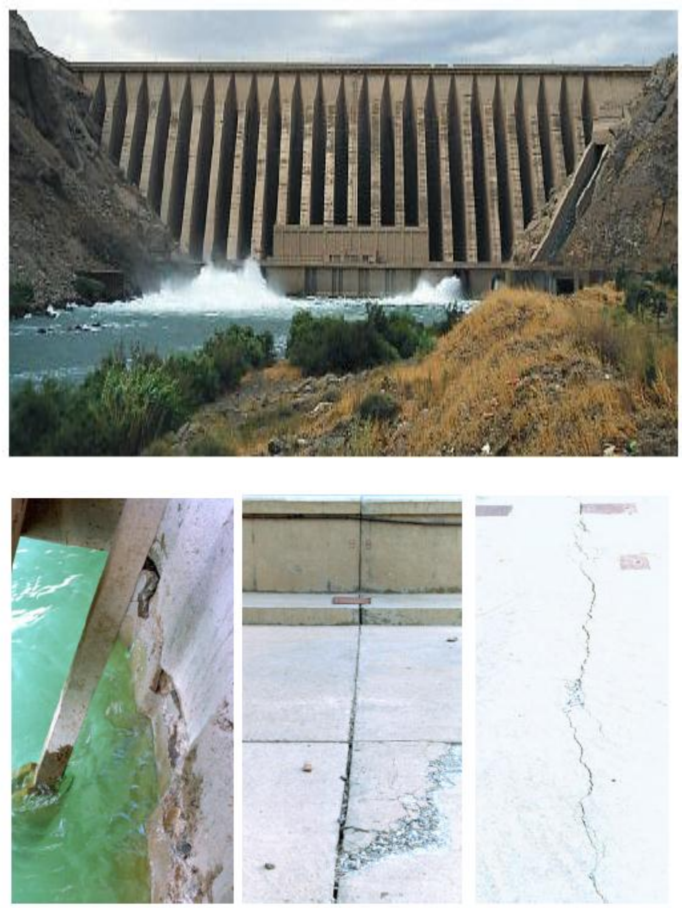

Fig. 4: Crack at upstream face of Sefid Rud buttress dam (left) and cracks in dam crest caused by the 1990 Manjil earthquake, Iran (Photos M. Wieland)

IV. Seismic Aspects Of Dam Design

(i) Seismic safety of existing dams: A large number of the existing dams were designed According to analytical possibilities prevailing at the time the respective dams were built. More precise knowledge on existing dam's safety (using up to date analyses) are 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. But 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 instrumentation of large dams.

(iii) Reservoir-triggered seismicity (RTS): An understanding of reservoir-triggered seismicity phenomena was reached during the 1970. 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. In general, RTS is not a safety problem for large dams designed according to the current ICOLD guidelines as the maximum RTS event is smaller than the maximum credible earthquake used for seismic dam safety evaluations.

(iv) Seismic risk determination and related techniques: One of the basic objectives in safety considerations are the determination of seismic risk for each particular dam. A review of the resulting seismic parameters is intended.

V. Dam Safety Aspects

Basically, the seismic safety of a dam depends on the following factors (Wieland, 2003):

(1) 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.

(2) 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. (The dams should be maintained properly including periodic inspections).

(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.

These basic safety elements are almost independent of the type of hazard. In general, dams, which can resist the strong ground shaking of the MCE, will also, perform well under other types of loads. In the subsequent sections, the emphasis will be put on the structural safety aspects, which can be improved by structural measures. Safety monitoring, operational safety and emergency planning are non-structural measures as they do not reduce the seismic vulnerability of the dam directly.

VI. Seismic Design Criteria For Large Dams

According to ICOLD Bulletin 72 (1989), large dams have to be able to withstand the effects of the MCE. This is the strongest earthquake that could occur in the region of a dam, and is considered to have a return period of several thousand years (typically 10'000 years in regions of low to moderate seismicity). The designer must take into account the motions resulting from any earthquake at any distance from the dam site, and possible movement of the foundation if a potentially active fault crosses the dam site. Having an active fault in the foundation is sometimes unavoidable, especially in highly seismically active regions, and should be considered as one of the most severe design challenges requiring special attention. It has to be kept in mind that each dam is a prototype structure and that the experience gained from the seismic behaviour of other dams has limited value, therefore, observations have to be combined with sophisticated analyses, which should reflect reality as close as possible. We also have to realize that earthquake engineering is a relatively young discipline with plenty of unsolved problems.

Therefore, every time there is another strong earthquake some new unexpected phenomena are likely to emerge, which have implications on regulations and codes. This is particularly true for dams as very few modern dams have actually been exposed to very strong ground motions. As mentioned earlier, the time of the pseudostatic design with a seismic coefficient of 0.1 has long passed. Of course, this concept was very much liked by designers because the small seismic coefficients being used did not require any special analyses and the seismic requirement could easily be satisfied. As a result, the seismic load case was usually not the governing one. This situation has changed and the earthquake load case has become the governing one for the design for most high risk (dam) projects, especially in regions of moderate to high seismicity.

VII. Earthquake Design Aspects Of Concrete Dams

There are several design details that are regarded as contributing to a favourable seismic performance of arch dams (ICOLD, 2001; Wieland, 2002), i.e.:

- Design of a dam shape with symmetrical and anti-symmetrical mode shapes that are excited by a long valley and cross-canyon components of ground shaking.
- Maintenance of continuous compressive loading along the foundation, by shaping of the foundation, by thickening of the arches towards the abutments (filets) or by a plinth structure to support the dam and transfer load to the foundation.
- Limiting the crest length to height ratio, to assure that the dam carries a substantial portion of the applied seismic forces by arch action, and that nonuniform ground motions excite higher modes and lead to undesired stress concentrations.
- Providing contraction joints with adequate interlocking.
- Improving the dynamic resistance and consolidation of the foundation rock by appropriate excavation, grouting etc.
- Provision of well-prepared lift surfaces to maximize bond and tensile strength.
- Increasing the crest width to reduce high dynamic tensile stresses in crest region.
- Minimizing unnecessary mass in the upper portion of the dam that does not contribute effectively to the stiffness of the crest.
- Maintenance of low concrete placing temperatures to minimize initial, heat-induced tensile stresses and shrinkage cracking.
- Development and maintenance of a good drainage system.

The structural features, which improve the seismic performance of gravity and buttress dams, are essentially the same as that for arch dams. Earthquake observations have shown that a break in slope on the downstream faces of gravity and buttress dams should be avoided to eliminate local stress concentrations and cracking under moderate earthquakes. The webs of buttresses should be sufficiently massive to prevent damage from cross-canyon earthquake excitations.

VIII. Assessment Of Seismic Design Of Embankment Dams

Basically, the seismic safety and performance of embankment dams is assessed by investigating the following aspects (Wieland, 2003):

- Permanent deformations experienced during and after an earthquake (e.g. loss of freeboard);
- Stability of slopes during and after the earthquake, and dynamic slope movements;
- Build-up of excess pore water pressures in embankment and foundation materials (soilliquefaction);
- Damage to filter, drainage and transition layers (i.e. whether they will function properly after the earthquake);
- Damage to waterproofing elements in dam and foundation (core, upstream concrete or asphalt membranes, geotextiles, grout curtain, diaphragm walls in foundation, etc.)
- Vulnerability of dam to internal erosion after formation of cracks and limited sliding movements of embankment slopes, or formation of loose material zones due to high shear (Shear bands), etc.
- Vulnerability of hydro mechanical equipment to ground displacements and vibrations, etc.
- Damage to intake and outlet works (release of the water from the reservoir may be endangered).

The dynamic response of a dam during strong ground shaking is governed by the deformational characteristics of the different soil materials. Therefore, most of the above factors are directly related to deformations of the dam. Liquefaction phenomena are a major problem for tailings dams and small earth dams constructed of or founded on relatively loose cohesion less materials, and used for irrigation and water supply schemes that have not been designed against earthquakes. This can be assessed based on relatively simple in situ tests. For example, there exist empirical relations between SPT blow counts and liquefaction susceptibility for different earthquake ground motions, which are characterized by the number of stress cycles and the ground acceleration.

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For large storage dams, the earthquake-induced permanent deformations must be calculated. Damage categories are, e.g., expressed in terms of the ratio of crest settlement to dam height. The calculations of the permanent settlement of large rockfill dams based on dynamic analyses are still very approximate, as most of the dynamic soil tests are usually carried out with maximum aggregate size of less than 5 cm. This is a particular problem for rockfill dams and other dams with large rock aggregates and in dams, where the shell materials, containing coarse rock aggregates, have not been compacted at the time of construction. Poorly compacted rockfill may settle significantly during strong ground shaking but may well withstand strong earthquakes.

To get information on the dynamic material properties, dynamic direct shear or triaxial tests with large samples are needed. These tests are too costly for most rockfill dams. But as information on the dynamic behaviour of rockfill published in the literature is also scarce, the settlement prediction involves sensitivity analyses and engineering judgment.

Transverse cracking as a result of deformations is an important aspect. Cracks could cause failure of embankment dams that do not have filter, drain and transition zones; or have filter, drain and transition zones that do not extend above the reservoir water surface; or modern filter criteria were not used to design the dam.

IX. CONCLUSIONS

The field of earthquake engineering of large dams is still a relatively young discipline with limited observational data. Information is mainly needed on the behaviour of dams subjected to very strong ground shaking, which cannot be predicted reliably with the present computer simulations. It has to be expected that after each strong earthquake, new phenomena are likely to emerge, which may require modifications of the current seismic design criteria for dams. It has to be realized that many of the large dams planned in Turkey, Iran, Central Asia, Pakistan, India, Nepal, Bhutan, Myanmar and the Southwest of China etc. are located in zones of relatively high seismicity. Thus it can be expected that the seismic action will become the governing load case for many new dams. Moreover, the requirement that dams have to be able to resist the ground shaking of the MCE, will lead to greater importance of the seismic load case even for regions of low to moderate seismicity. We must also recognize that dams, which can resist strong earthquakes, are also stronger dams that will perform very well under other types of action and hazards.

Concrete and embankment dams of all types can be designed and constructed to satisfactorily resist earthquake loadings in areas of high seismicity. Experience shows that modern dams that have been shaken by strong earthquakes have experienced good performance. Most of the dams constructed before the 1980s have been designed against earthquakes by methods, which are considered as obsolete today. Therefore, a comprehensive seismic evaluation program has to be undertaken, to bring the safety of the existing dams up to modern seismic safety standards. Dams, which are seismically deficient and pose a great seismic risk, would either have to be strengthened or their reservoirs have to be lowered to achieve an acceptable earthquake safety. Besides structural safety, the earthquake risk of a large dam can be reduced by (i) seismic safety monitoring with e.g. strong motion instruments, and (ii) emergency planning for worst-case scenarios, which includes a water alarm system, evacuation plans and a team of dam and earthquake experts, who can assess the safety of a dam after a strong earthquake.

Seismic safety evaluation is carried out on the basis of MCE, MDE or SEE. During these events, cracks will develop and joints will open in concrete dams. Most of the deformations in a concrete dam are due to deformations at joints and cracks. For the safety check, the dynamic stability of detached concrete blocks has to be verified. Relatively simple rigid body models can be used to analyze the rocking and sliding motion of detached concrete blocks. Well-designed and properly compacted CFRDs on rock foundations are considered safe under the strongest earthquake loading. This is because the width of the cracks in the face slab that may develop as a result of high dynamic stress and deformations, predicted from a traditional two-dimensional dynamic analysis of the highest dam section, are relatively small and thus the resulting leakage does not impair the safety of the dam. However, the behaviour of the concrete face during a strong earthquake is largely unknown, especially when looking at the cross-canyon excitation, which up to now has been largely ignored because of its complexity.

Diaphragm walls and grout curtains have also to be considered in the overall seismic design of a dam as damage caused to these elements may have detrimental effects on the overall safety of the dam after a severe earthquake.

REFERENCES

[1] Committee on Seismic Aspects of Dam Design, ICOLD, Paris

[2] Engineering, Editors: M. Wieland and J.S.Y. Tan, CI Premier Pte Ltd., Singapore, March 20-22, 2002

[3] International Commission on Large Dams; Proc. 21st Congress of ICOLD, Montreal, Canada, june 16-20, 2003

[4] ICOLD Bulletin 72 (1989): Selecting Seismic Parameters for Large Dams, Guidelines, Committee on Seismic Aspects of Dam Design, ICOLD, Paris

[5] ICOLD Bulletin 72 (1989): Selecting Seismic Parameters for Large Dams, Guidelines, committee on Seismic Aspects of Dam Design, ICOLD, Paris

[6] Rockfill dams, 13th World Conf. on Earthquake Engineering, Paper 3399, Vancouver, Canada, Aug. 2004

[7] Wieland M. (2003): Seismic aspects of dams, General Report Question 83: Seismic aspects of dams

[8] Wieland M., Brenner R.P. (2004): Earthquake aspects of roller compacted concrete and concrete-face

[9] Wieland M., Brenner R.P. (2005): Earthquake aspects of concrete-face rock fill dams, diaphragm walls and grout curtains, Proc. Symposium on CFRD & 20th Anniversary of China's CFRD. Construction Yichang, China, Sept. 19-24, 2005;