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Seismic Evaluation of Concrete Dams

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Résumé

L'activité sismique dans le voisinage des barrages est une question qui mérite un examen sérieux, car la rupture d'un barrage pourrait être désastreuse, au niveau tant des pertes de vie que des dommages matériels. Ce document vise à présenter un aperçu des méthodes utilisées pour l'évaluation sismique des barrages-poids et des barrages-voûtes en béton. Les principaux aspects étudiés sont : les critères d'évaluation, l'apport sismique et les modèles d'analyse dynamique des systèmes barrage-réservoir-fondation. Il est fait allusion à l'analyse non linéaire. En conclusion, les auteurs indiquent les axes des recherches qu'il importera au plus haut point d'accomplir dans l'avenir si l'on veut disposer de procédures détaillées d'évaluation sismique des barrages. Ils situent les grands barrages-poids et barrages-voûtes canadiens (plus de 60 m de hauteur) par rapport aux zones sismiques du CNBC 1985.

SEISMIC EVALUATION OF CONCRETE DAMS

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ABSTRACT

Seismic activity in the vicinity of dams is an important factor that should be carefully considered as the failure of a dam could be disastrous both in terms loss of life and property. The purpose of this paper is to present a brief survey of methods used for seismic evaluation of concrete gravity and arch dams. The principal aspects addressed are: evaluation criteria, seismic input, and models for dynamic analysis of dam-reservoir-foundation systems. Reference is briefly made to nonlinear analysis. The paper concludes by highlighting future research areas that are of primary importance in having comprehensive procedures for seismic evaluation of dams. Locations of large Canadian gravity and arch dams (over 60 m in height) with respect to seismic zoning of the NBCC 1985 are presented.

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INTRODUCTION

The consequences of the failure of a major dam are of such proportions that they must be ruled out by proper design and maintenance. Seismic activity in the vicinity of the dam is one of the natural environmental factors that needs to be carefully considered. Seismic safety of dams has a large bibliography and several reviews have been carried out [2,3,4,5]. Several countries including the U.S. have federal or government agency programs for safety evaluation of existing dams. Canada, however, has programs administered by provincial utility companies with one exception: the provincial government program in Alberta.

The 1984 register of Canadian dams listed 175 large concrete dams which are over 15 m in height. Among these, 155 were of the gravity type and only 4 were arch dams [5]. Table 1 presents seventeen large Canadian dams over 60m in height, including some technical data [5]. A majority of these dams are located in Zone 3 or 4 of the NBCC 1985 [6], with maximum predicted accelerations 0.11g and 0.16g, respectively, with a return period of 475 years (Fig. 1). Most of the dams are closely supervised by provincial hydro and utility organizations. Safety assessment of existing dams for earthquake conditions is also an objective for a recent study by the Canadian Electrical Association (CEA) [7]; similar studies have been carried out by the Electrical Power Research Institute (EPRI) in the U.S.A.

This paper presents a brief survey of seismic evaluation criteria of concrete gravity and arch dams. The following aspects are addressed:

1. Seismic safety evaluation criteria of several U.S. agencies
2. Seismic input to dam structures
3. Engineering models for dam-reservoir-foundation systems (BEM and FEM)

The paper also includes an update on some recent developments and highlights further needed research topics.

EXISTING EVALUATION CRITERIA

A comprehensive review of the state-of-the-art on the dynamic and earthquake behaviour of concrete dams was presented by Hall [8]. It includes U.S., Chinese, Japanese, European (Italy, U.K., Austria, Switzerland, Yugoslavia, Romania, Portugal and Spain) and experiences from other countries (India, Taiwan, Russia). Hall points out that although no concrete dam has ever failed as a result of an earthquake, as far as is known, never has a large concrete dam with completely full reservoir (i.e. maximum water level) been subjected to strong ground motions.

The U.S. has a long tradition in dam engineering and some U.S. agencies have developed criteria or programs for evaluating the seismic safety of concrete dams. Following is a brief summary of procedures used by four major agencies:

(1) The U.S. Army Corps of Engineers gives the criteria for evaluation of concrete dams in Engineer Technical Letter (ETL) 1110-2-303 [9]. These constitute additional requirements to the pseudostatic dam analysis, which is the standard method of analysis by the U.S. Army Corps of Engineers. The criteria could be summarized in the following steps:

1. As a first check, a pseudostatic analysis using a seismic coefficient should be carried out (based on seismic zoning map).
2. A dynamic analysis should be carried out where a specific dam failure could lead to the loss of many lives and one of three conditions exists:
   a) The dam height is greater than 100 feet (approx. 30.5 m) and the predicted ground acceleration for the so-called maximum credible earthquake (MCE) is greater than 0.20g.
   b) The dam height is less than 100 feet (approx. 30.5 m) and the maximum credible earthquake (MCE) has ground acceleration greater than 0.40 g.
   c) The static or pseudostatic seismic stability criteria are not fulfilled.

The U.S. Army Corps of Engineers recommends for dynamic analysis the simplified method proposed by Chopra [10] or the finite element method by means of commercial computer programs. They consider linear analyses only.

(2) The U.S. Federal Emergency Management Agency (FEMA) has included evaluation criteria for existing dams in Federal Guidelines, for Earthquake Analyses and Design of Dams [11]. These criteria recommend use of approximate pseudo-static methods as a first step and later application of more refined methods of analysis based on FEM. More refined analysis should be carried out based on engineering judgment, taking into account seismicity of a specific dam site, the height of dam, the existing geotechnical conditions and material properties. The FEMA guidelines make reference to all three types of methods: pseudo-static, response spectrum and time history.

(3) Criteria for dam safety have also been a prime objective for the Department of Water Resources, Division of Safety of Dams (DSOD), State of California [12]. DSOD has supervision of 1185 dams falling under the jurisdiction of local governments in California and are under public or private ownership. DSOD has responsibility for review and approval of design of new dams and for evaluation of existing dams. This program was established after a failure of St. Francis Dam on March 12, 1928 due to the massive landslide which developed on the left abutment. DSOD inspects most dams annually and also monitors

development of new dam sites. Approximately 25% of all dams (340) are instrumented with strong motion seismographs. In case of a seismic event, an owner of a dam is notified immediately. An owner should provide DSOD with all necessary studies during the evaluation process which is later approved by DSOD. DSOD also owns a special computer program QUAKE which assigns an earthquake to a given dam site. Site specific parameters for evaluation purpose include:

1. Causative fault or faults
2. Maximum Credible Earthquake (MCE), Richter magnitude and epicentral distance to site
3. Peak ground acceleration (PGA)
4. Duration of strong motion (amplitudes above 0.05 g)
5. Predominant period of ground motion.

DSOD specifically requires three-dimensional finite element modelling for arch dams. The analysis can be linearly elastic. Response spectrum or time history analyses need to be used.

(4) Pacific Gas and Electric Co. (PGE) based in California owns, operates and maintains over 100 dams in Northern and Central California [13]. Among them are 34 concrete dams, 19 concrete gravity dams and 15 concrete arch dams. These dams are regulated under jurisdiction of the DSOD and also must comply with federal requirements by FEMA and the Federal Energy Regulatory Commission (FERC). Although PGE participates in annual inspections by DSOD and FERC, a separate dam safety program was established. Program objectives are to inspect and evaluate PGE dams and to report all required information to state and federal regulatory bodies.

The principal method used by PGE is the pseudo-static method with updated pseudo-static coefficients according to regional seismicity studies. PGE recommends also use of the simplified Chopra method [15,16] based on a linear elastic response spectrum approach that includes dam-foundation interaction and dam flexibility in an approximate manner, or a time history finite element analysis. In the response spectrum analysis, maximum stresses for each mode are calculated and then superimposed to give a maximum stress distribution. In a time history finite element analysis, stresses are calculated based on the ground motion time history. For arch dams, PGE recommends finite element analyses based on commercial FEM programs like SAPIV, STRUDL, GSTRUDL, SAP80 or a two-dimensional program EAGD-84 developed by Chopra et al. at the University of California at Berkeley [10,21].

SEISMIC INPUT

A dam may be subjected to two types of earthquakes: natural earthquakes in known seismic areas and reservoir-induced earthquakes.

A statistical study by Haws and Reilly [2] reveals that so far only embankment dams have collapsed or been severly damaged during natural earthquakes. They include Eklutna Dam in Alaska, Lower San Fernando Dam (known also as Van Norman Dam), and Sheffield Dam in England (see Table 2). Surprisingly, more damaging to large concrete structures were the reservoir-induced earthquakes, as presented in Table 3. Five of the clearest cases of induced earthquakes are Lake Kariba in Zimbabwe and Zambia border in Central Africa, Koyna in India, Hsinfengkiang in China, Nurek in the Soviet Union and Aswan in Egypt. At Koyna, in addition to significant cracking of the dam, a large number of people were killed by the Magnitude 6.5 earthquake. At the Hsinfengkiang dam, the principal shock of a Magnitude 6.1 earthquake in 1962 caused major cracking.

An estimate of the seismic input to the specific dam site is a crucial part of the engineering analysis and evaluation process. The most common measures used as inputs are peak accelerations, response spectra, and ground acceleration histories. Ground motion characteristics are usually a function of earthquake magnitude and epicentral distance. Seismic inputs should be carefully chosen for both linear elastic and the non-linear analyses in the evaluation process.

In the U.S. as in many other parts of the world, two levels of earthquake input are usually considered in investigating the seismic safety of a dam [12]:

1. The Maximum Credible Earthquake (MCE) is the earthquake associated with the specific site that would cause the strongest expected ground motion or fault rupture under the foundation. It is usually chosen to be the worst scenario with a very low probability of occurrence.

2. The Operating Basis Earthquake (OBE) is a typical earthquake for the particular site with a higher probability of occurrence.

Both the MCE and OBE are usually provided by the U.S. Geological Survey. The Richter magnitudes for the MCE have been established for most faults in California [14].

Variation of seismic motion throughout canyons is still unresolved. So far, all methods of evaluation have used a spatially uniform seismic input to the foundation of a dam.

ENGINEERING MODELS OF DAM-RESERVOIR-FOUNDATION SYSTEMS

Generally, two types of engineering models are used in the dynamic analysis of dam-reservoir-foundation systems: two-dimensional models used for concrete gravity dams and three-dimensional models used for arch dams. In these models, the dam is usually represented by an assemblage of finite elements and the reservoir is also modelled by finite elements or in some cases by boundary elements. Displacements are the unknowns for a dam and pressures are the unknowns for a reservoir. A summary of the state-of-the-art on FEM modelling of both concrete gravity and arch dams can be found in Ref. 10. In the eighties, simplified solutions, based on response spectra analysis, of the problem of seismic response of these complex systems have been developed [15,16]. These solutions include effects of dam-foundation and dam-reservoir interactions. The FEM modelling is considered essential when the detailed dynamic analysis of this complex system is required. This is especially needed when one of the simplified analyses fails to meet standard requirements for seismic stability of the dam [10,14].

Several important factors can be taken into account in a full FEM analysis, the principal ones being:

1. Dam-reservoir interaction effect on hydrodynamic pressures.
2. Energy loss due to outgoing waves using a special transmitting boundary for an infinite reservoir.
3. Dissipation of the energy in a reservoir by absorptive soil in the reservoir bottom.
4. Interaction between dam and foundation in the immediate vicinity of a dam.

The above listed factors were included in the FEM linear models of dam-reservoir-foundation systems [17,18,19,20,21], and also (with the exception of the last factor) by BEM [22,23]. All of them are frequency domain models; thus they could not include nonlinear material behaviour of the dam or foundation nor could they encompass the important problem of concrete cracking.

True non-linear analyses should be performed directly in the time domain, i.e. using step-by-step time integration methods. There are two methods for analyzing this type of problem in the time domain [24] : the substructure method and the direct method. In the substructure method the system is divided into two parts: (i) the dam itself and adjoining parts of the infinite media which may be non-linear and/or geometrically irregular, (ii) the remaining infinite part of the system which is assumed to be linearly elastic. The structure part is discretized as usual by using finite elements; the infinite part is represented by its dynamic stiffness or influence matrix that could be formulated indirectly in the frequency domain [24,25] or directly in the time domain using an extensive FEM mesh [26]. The force contribution to the structure of the infinite part is calculated by means of discretized convolution integrals of the boundary matrix of the infinite part and the corresponding boundary displacements (see for example [24,25]). The substructure method takes into account all interaction effects and wave propagation in the infinite part rigorously and hence is very accurate. However, the computational effort of this method is substantial. The direct method, on the other hand, is more economical, but the wave propagation towards infinity, i.e. the radiation condition, is taken into account only approximately. The finite element model consists of the structure (as defined above) and a small part of the linear infinite medium. The remaining infinite part of the system is approximately simulated using a frequency-independent wave-absorbing boundary [24]. In both the substructure and the direct method, arbitrary seismic input can be easily applied using the so-called effective seismic input method [27].

FURTHER RESEARCH

In spite of the fact that substantial accomplishments have been made in the last few years [e.g. 28-37], a number of problems remain unsolved. Further progress in the following research areas has been repeatedly stated in the literature as important:

- Variation of seismic input motions over the dam-foundation interface especially for the case of arch dams.

- Development of the substructure method in which the radiation condition in the reservoir and foundation rock can be rigorously and consistently taken into account.

- Experimental studies of the properties and constitutive behaviour of concrete under multiaxial dynamic conditions.

- Non-linear analysis procedures to take into account crack initiation and propagation, gradual crack opening, opening and closing of construction joints, sliding along weak planes, etc.

- Monitoring of existing dams located in highly seismic regions using strong motion instrumentation to provide benchmark cases for the validation of analytical methods.

- Testing of physical models of dams using shaking tables and centrifuge apparatus to investigate failure modes and evaluate analytical methods.

The result of these component studies would permit the development of comprehensive evaluation procedures.

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Table 1. Concrete Gravity and Arch Dams in Canada Exceeding 60 Metres in Height

No.	Name of Dam	Year(1)	Location: River	Location: Nearest City	Location: Prov.	Type of Dam	$H^{(2)}$	$L^{(3)}$	$V^{(4)}$	Gross capacity of reservoir $[10^3\ m^3]$	Owner of dam
1	Daniel Johnson	1968	Manicouagan	Baie-Comeau	PQ	Multiarch	214	1,314	2,255	141,851,350	Hydro-Quebec
2	Revelstoke	1983	Columbia	Revelstoke	BC	Gravity, rock fill	175	470	1,600	5,180,000	B.C. Hydro
3	Lower Notch	1971	Montreal	North Bay	ON	Gravity, rock fill	132	1,969	1,837	170,960	Ontario Hydro
4	Abitibi Canyon	1933	Abitibi	Cochrane	ON	Gravity	106	259	710	45,639	Ontario Hydro
5	Cleveland	1954	Capilono	Vancouver	BC	Gravity	92	195	110	75,243	Greater Vancouver Water District
6	Manicouagan 2	1965	Manicouagan	Baie-Comeau	PQ	Gravity	91	692	745	4,248,140	Hydro-Quebec
7	Bersimis II, Main	1959	Bersimis	Labrieville	PQ	Gravity	84	643	779	1,614,002	Hydro-Quebec
8	Outardes 3	1968	Outardes	Baie-Comeau	PQ	Gravity	84	299	362	207,226	Hydro-Quebec
9	Seven Mile	1980	Pend d'Oreille	Trail	BC	Gravity	79	348	305	86,350	B.C. Hydro
10	Manicouagan 3 - Evacuateur de crues	1975	Manicouagan	Baie-Comeau	PQ	Gravity	76	282	382	10,422,991	Hydro-Quebec
11	Waneta	1954	Pend d'Oreille	Trail	BC	Gravity	76	290	240	37,621	Cominco Ltd.
12	Beaumont	1959	St.-Maurice	La Tuque	PQ	Gravity	72	405	242	424,321	Hydro-Quebec
13	Grand Rapides	1965	Saskatchewan	The Pas	MT	Gravity, rock fill	66	24,018	7,133	9,643,425	Manitoba Hydro
14	Trenche	1951	St.-Maurice	La Tuque	PQ	Gravity	65	442	352	317,007	Hydro-Quebec
15	Lois (Scanlan)	1941	Lois	Powell River	BC	Arch	64	229	not known	555,071	MacMillan, Bloedel & Power
16	Peace Canyon	1980	Peace	Hudson Hope	BC	Gravity, rock fill	63	533	532	215,860	BC Hydro
17	Rayner George W	1950	Mississagi	Sault Ste. Marie	ON	Gravity	61	351	142	191,191	Ontario Hydro

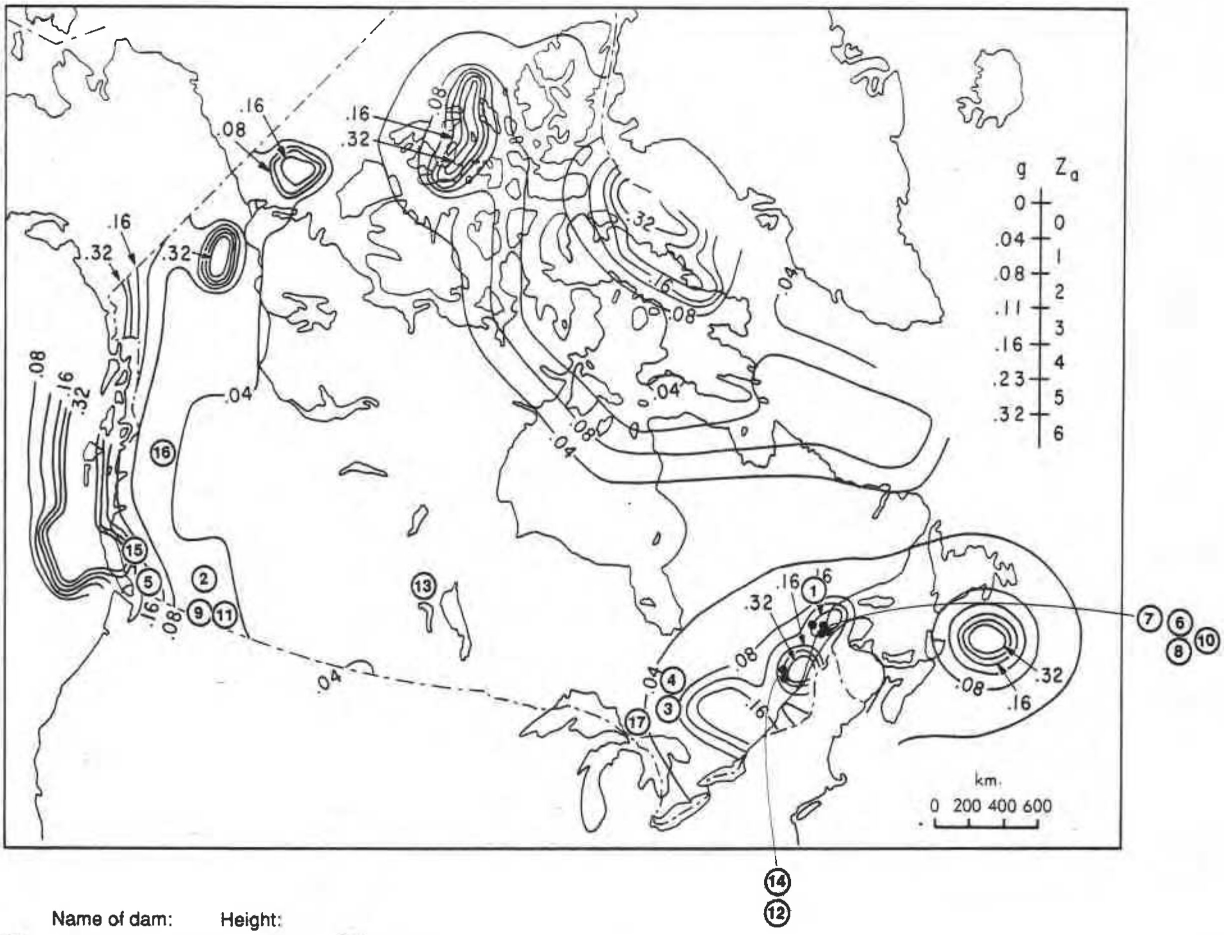
(1) Year of Completion
(2) Height above dam foundation [m]
(3) Length of crest [m]
(4) Volume content of dam $[10^3 m^3]$

Table 2. Some Dams Subjected to Natural Earthquakes (after Haws and Reilly [3])

No.	Name of Dam	Country	Type of Dam	Height [m]	Built	Earthquake Date	Earthquake M	Damage
1	Sheffield	USA	Embankment	8	1917	1925	6.3	Collapse
2	Eklutna	USA	Embankment	6	1929		8.5	Severe
3	Lower San Fernando	USA	Embankment	42	1912/30	1971	6.5	Very Severe
4	Upper San Fernando	USA	Embankment	25	1921	1971	6.5	Serious
5	Hebyen Dam	USA	Embankment	37	1915	1959		Serious
6	El Doldado	Chile	Tailing Dam			1965	7.1	Collapse
7	On Izu Pennisula	Japan	Tailing Dam			1978	5.7	Failure
8	Baihe	China	Embankment	60		1976	7.8	Serious

Table 3. Some Dams Subjected to Reservoir-Induced Earthquakes (after (3,10))

No.	Name of Dam	Country	Type of Dam	Height [m]	Res. Volume [106m3]	Impounding Date	Largest Earthquake M	Largest Earthquake Year
1	Marathon	Greece	Gravity	63	41	1930	5.0	1938
2	Hoover	USA	Arch, gravity	221	36,703	1936	5.0	1939
3	Kariba	Zimbabwe/ Zambia	Arch	128	160,368	1959	5.8	1963
4	Hsinfengkiang	China	Concrete Buttress	105	10,500	1959	6.1	1962
5	Koyna	India	Concrete Gravity	103	2,708	1964	6.5	1967
6	Aswan	Egypt	Embankment	111	169,000	1964	5.6	1981
7	Kremasta	Greece	Embankment	165	4,750	1965	6.3	1966
8	Roi Constantine	Greece	Embankment	96	1,000	1969	6.3	1970
9	Nurek	USSR	Embankment	300	10,500	1971	4.6	1972



	Name of dam:	Height:			
1	Daniel Johnson	214 m	11	Waneta	76 m
2	Revelstoke	175 m	12	Beaumont	72 m
3	Lower Notch	132 m	13	Grand Rapids	66 m
4	Abitibi Canyon	106 m	14	Trenche	65 m
5	Cleveland	92 m	15	Lois (Scanlon)	64 m
6	Manicougan 2	91 m	16	Peace Canyon	63 m
7	Bersimis II, Main	84 m	17	Rayner George W.	61 m
8	Outardes 3	84 m			
9	Seven Mile	73 m			
10	Manicougan 3	76 m			

Z_a = 0 - 6, seismic zones in Canada

g = acceleration due to gravity

FIGURE 1

LOCATION OF LARGE GRAVITY DAMS WITH RESPECT TO SEISMIC ZONES IN CANADA [6]