Engineering 2 (2016) 325–331

Contents lists available at ScienceDirect

Engineering

journal homepage: www.elsevier.com/locate/eng

Research
Hydro Projects—Review

Safety Aspects of Sustainable Storage Dams and Earthquake Safety of Existing Dams

Martin Wieland [a,b]

[a] Committee on Seismic Aspects of Dam Design, International Commission on Large Dams, Paris 75116, France
[b] Poyry Switzerland Ltd., Zurich 8048, Switzerland

ARTICLE INFO

Article history:
Received 7 April 2016
Revised form 29 June 2016
Accepted 24 August 2016
Available online 19 September 2016

Keywords:
Dams
Earthquake design
Earthquake safety
Existing dams
Design criteria
Seismic hazard
Sustainability
Service life

ABSTRACT

The basic element in any sustainable dam project is safety, which includes the following safety elements: ① structural safety, ② dam safety monitoring, ③ operational safety and maintenance, and ④ emergency planning. Long-term safety primarily includes the analysis of all hazards affecting the project; that is, hazards from the natural environment, hazards from the man-made environment, and project-specific and site-specific hazards. The special features of the seismic safety of dams are discussed. Large dams were the first structures to be systematically designed against earthquakes, starting in the 1930s. However, the seismic safety of older dams is unknown, as most were designed using seismic design criteria and methods of dynamic analysis that are considered obsolete today. Therefore, we need to reevaluate the seismic safety of existing dams based on current state-of-the-art practices and rehabilitate deficient dams. For large dams, a site-specific seismic hazard analysis is usually recommended. Today, large dams and the safety-relevant elements used for controlling the reservoir after a strong earthquake must be able to withstand the ground motions of a safety evaluation earthquake. The ground motion parameters can be determined either by a probabilistic or a deterministic seismic hazard analysis. During strong earthquakes, inelastic deformations may occur in a dam; therefore, the seismic analysis has to be carried out in the time domain. Furthermore, earthquakes create multiple seismic hazards for dams such as ground shaking, fault movements, mass movements, and others. The ground motions needed by the dam engineer are not real earthquake ground motions but models of the ground motion, which allow the safe design of dams. It must also be kept in mind that dam safety evaluations must be carried out several times during the long life of large storage dams. These features are discussed in this paper.

1. Introduction

The basic element in any sustainable structure or infrastructure project is safety. Therefore, for sustainable storage dams, the emphasis must be on the long-term safety of the dam. Today, dam safety requires an integral safety concept, which comprises the following elements:

- Structural safety;
- Dam safety monitoring;
- Operational safety and maintenance; and
- Emergency planning.

Long-term safety primarily includes the analysis of all hazards affecting the project; that is, hazards from the natural environment, hazards from the man-made environment, and project-specific and site-specific hazards. This paper discusses the special features of the seismic safety of dams, as the structural safety of large storage dams today is often governed by the earthquake load case.

For large dam projects, a site-specific seismic hazard analysis is usually recommended. These analyses are carried out by seis-

E-mail address: martin.wieland48@gmail.com

http://dx.doi.org/10.1016/J.ENG.2016.03.011

mologists. It is important that the dam engineer, who is the end user of the results of seismic hazard analyses, clearly specifies what he or she needs, as seismologists are not familiar with the seismic safety concepts used in dam engineering. Today, large dams and the safety-relevant elements used for controlling the reservoir after a strong earthquake (such as the gates of gated spillways and the gates of bottom outlets) must be able to withstand the ground motions of the safety evaluation earthquake (SEE). The SEE ground motion parameters can be determined either by a probabilistic seismic hazard analysis (PSHA) or by a deterministic analysis in which worst-case earthquake scenarios are considered. During the SEE, inelastic deformations may occur in a dam; therefore, the seismic analysis must be carried out in the time domain. In general, seismologists provide response spectra or uniform hazard spectra as the result of their seismic hazard studies, but acceleration time histories are needed for the inelastic analysis of large dams. In addition, earthquakes create multiple seismic hazards for dams such as ground shaking, fault movements, mass movements, and other project-specific and site-specific hazards. Reservoir-triggered seismicity (RTS) may also have to be considered.

The ground motions needed by the dam engineer—that is, mainly the acceleration time histories—are not real earthquake ground motions but models of the ground motion, which allow the safe design of dams.

Furthermore, it must be kept in mind that dam safety evaluations have to be carried out several times during the long life of large storage dams.

The state-of-practice in the seismic analysis and design of dams is documented in the bulletins and guidelines [1–5] prepared by the Committee on Seismic Aspects of Dam Design of the International Commission on Large Dams (ICOLD). These are:

- Bulletin 112: Neotectonics and dams [1];
- Bulletin 120: Design features of dams to effectively resist seismic ground motion [2];
- Bulletin 123: Earthquake design and evaluation of structures appurtenant to dams [3];
- Bulletin 137: Reservoirs and seismicity—state of knowledge [4]; and
- Bulletin 148: Selecting seismic parameters for large dams [5].

Bulletins 112 and 137 are concerned with dams on faults and with RTS, respectively; that is, with special features of seismic hazard for dams. Bulletins 120 and 123 provide guidelines on seismic design concepts and constructional features for the seismic design of a dam, which will perform satisfactorily during strong earthquakes. Bulletin 148 provides updated seismic design guidelines for dams, safety-relevant elements, and appurtenant structures.

The safety-relevant elements are spillway gates and bottom outlets, which must function after an earthquake in order to control the water level in the reservoir and, in the case of damage, to lower the reservoir so that the dam can be repaired and/or strengthened.

The current paper is based on publications prepared by the ICOLD Committee on Seismic Aspects of Dam Design [1–5] and on papers published by the author [6–9]. It provides an overview of seismic hazard, seismic design and performance criteria, seismic safety of existing dams, and sustainability of large storage dams.

2. Seismic hazard

An earthquake hazard is a multi-hazard, which includes the following main hazards for a large dam project [9]:

- Ground shaking;
- Movements along faults or discontinuities in the footprint of the dam and/or the reservoir;
- Mass movements into the reservoir causing impulse waves and increase in reservoir level, damaging transmission lines, blocking access roads, and so forth; and
- Project-specific and site-specific hazards (i.e., ground deformations, seepage, liquefaction, etc.).

Ground shaking is usually considered to be the main seismic hazard. However, movements in the footprint of a concrete dam are more critical than ground shaking, as any such movements would, for example, cause a complicated crack pattern in highly statically indeterminate arch dams, which cannot be reliably predicted by numerical models. The dynamic behavior of the dam would become very complex, as cracking in the dam due to foundation movement and ground shaking would occur at the same time. Therefore, the possibility of foundation movements must be studied carefully. Even if no seismogenic fault crosses the dam foundation, a strong earthquake at a nearby fault can cause movements along discontinuities in the footprint of a dam. These discontinuities are faults, shear zones, fissures, joints, and bedding planes. Such movements are hard to estimate because they depend on the site conditions, the distance from the seismically active fault, and its maximum surface movement. Some faults may also splay near the surface and reactivate discontinuities.

Conservatively designed earth core rockfill dams can cope with such movements, whereas arch dams will be very vulnerable to them. Therefore, if there is doubt regarding the possibility of fault movements, a conservatively designed earth core rockfill dam is the appropriate solution [1,2].

Mass movements into the reservoir would create impulse waves, which may overtop the dam crest. Here, concrete dams would be more suitable than embankment dams in order to resist limited overtopping. However, with an ample freeboard, a wide dam crest, and/or an upstream parapet or wave wall, this overtopping hazard can be reduced or even eliminated.

Moreover, mass movements in the reservoir region will increase the sediment volume in the reservoir and may block the bottom outlet. However, this will usually happen in the months or years after an earthquake, leaving time for remedial action.

Rockfalls in mountainous regions could damage transmission towers, which would lead to the automatic shut-down of the power plant. However, a more critical issue would be rockfall damage of the gate control structures, equipment, emergency power generators, control units, and so forth needed for the operation of the gates of spillways and bottom outlets. These gates have to be operable after a strong earthquake because it must be possible to control or lower the reservoir and release a moderate flood after a strong earthquake. Again, if these gates are blocked, it would lead to overtopping of the dam crest, which would be a much more serious safety problem for embankment dams than for concrete dams.

Therefore, it can be concluded that input is needed from seismologists and geologists on ① ground shaking, ② movements in the footprint of a dam (this is most important if a monolithic concrete dam is planned), and ③ critical slopes in the dam and reservoir region.

Usually, seismic hazard analyses are only concerned with the estimation of ground motion parameters such as peak ground acceleration (PGA) and response spectra. Ground motion parameters can be determined by a probabilistic and/or deterministic seismic hazard analysis, as discussed by Wieland [9] and ICOLD Bulletin 148 [5]. Accordingly, the dam body and the safety-relevant elements must be able to withstand the ground motion of the SEE with a return period of 10 000 years (probabilistic analysis) or the ground motions from worst-case earthquake scenarios (deterministic analysis). In the probabilistic analysis, the mean