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SEISMIC DESIGN AND PERFORMANCE CRITERIA FOR LARGE DAMS AND METHODS OF DYNAMIC ANALYSIS

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ABSTRACT

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The seismic design criteria for large dams and safety-critical elements, such as spillways and low level outlets that must function after a strong earthquake, are discussed. The ground motion parameters of the Safety Evaluation Earthquake (SEE) and Operating Basis Earthquake (OBE) are given. The general seismic performance criteria for large storage dams are presented, which today are mainly specified in terms of displacements for the worst ground motion to be expected at a dam site. For concrete dams the compressive stresses shall not exceed the compressive strength of concrete, which may be a limiting factor for slender arch dams. For the OBE the seismic performance criteria are given in terms of stresses and deformations. For the hydro-mechanical components of gated spillways and low level outlets mainly stress analyses will be needed in order to show that the equipment can be operated and will not be jammed by inelastic deformations. The seismic design criteria are given for dams with different risk classification and the corresponding methods of dynamic analyses for OBE and SEE ground motions are presented. In the past all seismic analyses were carried out by the pseudo-static method, which, today, is considered outdated and obsolete and shall no longer be used for large dams located in seismic areas. Today, the seismic stress and deformation analyses are carried out by linear dynamic analyses and dynamic stability analyses by rigid body analyses such as the Newmark sliding block method, which is standard practice for the slope stability analysis of embankment dams. New types of dams such as dams with thin impermeable membranes require a higher degree of accuracy in the analysis of deformation as these membranes may be vulnerable to dam deformations. Moreover, under the effect of strong earthquakes, dams may experience inelastic deformations, which are acceptable as long as the reservoir can be retained safely after the earthquake. A thorough understanding of the inelastic and nonlinear seismic phenomena, which are expected during strong ground shaking, is the prerequisite for any nonlinear seismic analysis of dams. The appropriate methods of dynamic analyses are discussed.

In a concrete dam, strong ground shaking could lead to opening of contraction joints and formation of cracks along horizontal lift joints, as a result of which high dynamic stresses are prevented in other parts of the dam. Similarly, embankment dams may undergo significant permanent deformations during a severe earthquake. For the seismic safety and damage assessment of concrete and embankment dams, nonlinear dynamic analyses are often needed to determine the expected inelastic deformations under the SEE.

The methods for nonlinear dynamic analysis of dams are, however, still under development. Nonlinear seismic analyses need substantial engineering judgment. The proper formulation of the goals of the seismic analysis is probably the most difficult task required to ensure that such an analysis can actually ‘succeed’. Relatively simple models should be preferred to complex models employing nonlinear constitutive laws using parameters that are either not available or very hard to determine.

1. INTRODUCTION – BACKGROUND ON SEISMIC ANALYSIS OF DAMS

Large dams were among the first structures, which were designed against earthquakes (Wieland, 2008a). The seismic analysis method developed by Westergaard in the 1930s for the Hoover arch-gravity dam has found worldwide acceptance among designers of concrete dams (Westergaard 1933). The seismic actions included in the stress and sliding stability analyses are the inertial effects of the dam body, equal to mass times the ground acceleration, and the hydrodynamic pressure acting on the vertical upstream face of a dam, obtained from the analytical solution of the pressure acting on a rigid vertical wall of a two-dimensional semi-infinite reservoir of constant depth, subjected to a harmonic horizontal ground acceleration. This analysis was done for both incompressible and compressible behaviour of the water, but in practice the simpler case of incompressible water was adopted, as in this case the maximum hydrodynamic pressure can be represented by an added mass that is attached to the upstream face of the dam multiplied with the peak ground acceleration, similar to the inertia force. In the seismic analysis it was assumed that these two horizontal earthquake loads are independent of time, which allowed a static analysis of a dam in which the dynamic properties such as eigenfrequencies, mode shapes and damping are ignored. This analysis is therefore referred to as pseudo-static analysis. It was common practice to use a seismic coefficient of 0.1, corresponding to a horizontal ground acceleration of 0.1 g, almost irrespective of the seismic hazard at a dam site, which was unknown in most cases, as dams are generally located in rather remote places.

At about the same time, the first earthquake analysis of an earth dam was made by Mononobe et al. (1936). They modeled the dam as an infinitely long symmetrical triangular section consisting of linear-elastic material and resting on a rigid foundation. However, general design practice at that time was to take account of the seismic loading of a dam by a seismic coefficient of 0.1. 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. If in a static slope stability analysis the factor of safety would approach unity, the dam would be considered close to failure and therefore unsafe. Because of its simplicity the pseudo-static slope stability analysis was well understood by engineers and used for the seismic design and safety assessment of dams. Two seismic load combinations were often considered: (i) earthquake occurring with full reservoir, and (ii) earthquake occurring after rapid reservoir drawdown. In most cases the rapid drawdown was critical, although, this case is not critical for the people living downstream of a dam. Anyway, if a dam is safe for the rapid drawdown case, it is safer than if it is only safe for the full reservoir case.

After the 1971 San Fernando earthquake in California it was recognized that the pseudo-static analysis method is not safe and not suitable for the prediction of the seismic safety of embankment dams subjected to strong ground shaking, and that it is necessary to account for the dynamic properties in the seismic design. That the dynamic properties play an important role on the seismic response of linear-elastic structures was known much earlier, but for dams, the San Fernando earthquake can be considered as the point in time when modern methods of seismic stress and deformation analyses as well as dynamic sliding stability analyses of embankment and concrete dams were applied. In 1989 ICOLD published a guideline on the selection of seismic design criteria for large dams (ICOLD 1989) in which two levels of earthquakes were defined for the seismic design and safety check of large dams, i.e. the operating basis earthquake (OBE) and the maximum design earthquake (MDE) with ground motion parameters obtained from a probabilistic seismic hazard analysis and the maximum credible earthquake (MCE) with ground motion parameters obtained from a worst-case scenario. Until then the seismic action was still characterized by a seismic coefficient and the pseudo-static analysis was used. However, already in 1986 an ICOLD guideline (ICOLD 1986) on earthquake analysis procedures for dams was published, which was written by O. C. Zienkiewicz and R. W. Clough - the main developers and inventors of the widely used finite element method -, and H. B. Seed, the main developer of analyses procedures for the seismic design and safety assessment of embankment dams. The first two authors worked mainly on concrete dams. The methods presented in that guideline are basically linear-elastic dynamic analyses, which are still used today.

Although the pseudo-static analysis concept is known to be unreliable and outdated (Wieland 2018a), it is still used today for seismic stability analyses, even in region of high seismicity. Despite of repeated calls for the use of more reliable methods of seismic analyses, especially for embankment dams, by the seismic committee of ICOLD, this unreliable and often unsafe method is unfortunately still widely used even in national guidelines for dams. It is sometimes argued that the pseudo-static method is used in building codes and therefore it should be ok for large dams as well, but there is a major difference between large dams and buildings; today, the return period of ground motion parameters of large dams is 10,000 years, whereas that for buildings is generally 475 years. From the analysis point of view the maximum seismic force acting on a rigid sliding body, the basic assumption for sliding stability analyses, is equal to the mass times the peak acceleration. But in practice a seismic coefficient is used, which has nothing in common with the peak ground acceleration. There is also no scientific basis for such relations. For embankment dams the so-called yield acceleration, i.e. the pseudo-static acceleration resulting in a sliding safety factor of 1.0, is typically in the range of 0.2-0.3 g, thus, at a site with a peak ground acceleration of 0.2-0.3, which is exceeded in regions of moderate to high seismicity, the sliding stability factor will drop to below 1.0, i.e. meaning that the slope or dam is unsafe. As there will be a dynamic amplification of the ground motion to the centre of gravity of the sliding mass, the sliding safety factor will drop even further. Because of this fact, pseudo-static accelerations that are much lower than the peak ground acceleration or the maximum acceleration at the location of the sliding mass are used. From the structural analysis point of view, this is not correct. However, if the sliding safety factor drops to below 1.0 it is not unsafe, it is only unsafe if the pseudo-static safety criteria are used, because if the safety factor drops to below 1.0 the sliding mass starts to slide. The stability of the slope must then be determined based on the sliding movement, which can be obtained from a dynamic sliding stability analysis proposed first time by Newmark in the 1960s. However, many engineers still like to stick to the simple pseudo-static concept, using unrealistically low seismic accelerations. This is not only a matter of engineers not being able to carry out more reliable seismic analyses of dams but also due to outdated seismic design specifications in some countries. The deficiencies of the pseudo-static analysis method – applied to dams - have been known since the 1971 San Fernando earthquake. That has been a very long time. To repeat, the physically correct way would be to use the peak acceleration at the location (i.e. the centre of gravity) of the rigid sliding mass in order to calculate the maximum inertia force.

Since 1989 more rational seismic design criteria are used, which require a dynamic analysis of dams. For concrete dams the simplest dynamic analysis method is the response spectrum method, in which the seismic input is given in form of an acceleration response spectrum. This method has been used to develop simplified dynamic analysis methods in which only the contributions of the dominant mode of vibration excited by an earthquake – usually the first mode – are taken into account. The simplified method developed by Chopra (1978) for gravity dams can be used for the safety check and design of small dams or the preliminary design of large dams. This approximate method is suitable for seismic stress analyses.

The response spectrum method was favored at the time when the computational resources were limited, because this method is very efficient when only a few modes of vibration have to be considered. This is the case for the dam deformations; however, for the equal accuracy of the stress response a larger number of modes must be included. It should also be mentioned that the response spectrum method only provides the maximum response and strictly speaking it is only applicable to linear-elastic structures with proportional damping. The response spectrum method is an approximate method for the calculation of the maximum dynamic response. Moreover, many cases have to be considered when the static and dynamic stresses have to be combined in a three-dimensional dam with 6 stress components. Actually 64 cases (2^6) would have to be considered for the absolute maximum seismic stresses. Because of these limitations and the fact that the computational resources are no longer any problem, it is recommended to use the direct time integration method for the dynamic analysis of dams and not the response spectrum or mode superposition method. In the direct time integration viscous damping is usually accounted for by Rayleigh damping, which is different from the modal damping used in the response spectrum method, where the same damping is usually assumed for all modes. In the Rayleigh damping model the higher modes have higher damping ratios than the lower ones. But damping is a property with a lot of uncertainties and dam analysts tend to use unrealistically high values in order to reduce the dynamic response of the dam.

In the response spectrum method the seismic input must be given in the form of acceleration response spectra, whereas for the time integration methods the seismic input is required in the form of acceleration time histories. Seismologists usually define the seismic hazard in terms of acceleration response spectra, typically for a damping ratio of 5%. This is still the case today, but nobody is using the response spectrum method anymore for large dams. Therefore, besides the response spectra, acceleration time records must be provided to the dam designer. The current practice is to use spectrum-matched acceleration time histories, i.e. the response spectrum of the acceleration time history must match the target response spectrum obtained from a site-specific seismic hazard analysis. Most seismologists are not really aware of what dam engineers need and dam engineers do not tell seismologists what they need from them. Hopefully this will change. Properties of spectrum-matched acceleration time histories are discussed in ICOLD (2016). These time histories are not real acceleration time histories, but models of the earthquake ground shaking, which, when used by dam engineers, will result in a safe design. This concept has been discussed by Wieland (2018b). It is an important issue, as it often leads to misunderstandings between seismologists and dam engineers.

Today, most dynamic analyses carried out are still linear-elastic analyses although by using modern seismic design criteria (ICOLD 2016) inelastic deformations of dams are accepted, i.e. nonlinear dynamic analysis methods are required, as discussed in the subsequent sections.

2. SEISMIC DESIGN AND PERFORMANCE CRITERIA FOR LARGE DAMS

In this Section an overview on the seismic design and performance criteria of large dams is given, which can be interpreted as a consequence of ICOLD Bulletin 148 on the selection of seismic parameters for large dams (ICOLD 2016). Accordingly, the two levels of earthquakes to be considered in the design and safety assessment of large existing dams are as follows:

- Operating Basis Earthquake (OBE): The OBE may be expected to occur during the lifetime of the dam. No damage or loss of service must happen. It has a probability of occurrence of about 50% during the service life of 100 years. The return period is taken as 145 years (ICOLD, 2016). The OBE ground motion parameters are estimated based on a probabilistic seismic hazard analysis. The mean values of the ground motion parameters of the OBE can be taken.
- Safety Evaluation Earthquake (SEE): The SEE is the earthquake ground motion a dam must be able to resist without uncontrolled release of the reservoir. The SEE is the governing earthquake ground motion for the safety assessment and seismic design of the dam and safety-relevant elements (gates and valves of spillways and bottom outlets, motors, emergency power supply, hydraulic pistons, etc.), which have to be functioning after the SEE in order to control the water level in the reservoir.

Today, the seismic performance criteria of dams are given in a rather general way for both the OBE and SEE:

- The following criteria apply for the OBE:
  - (i) Dam body and foundation: No structural damage in dam is accepted; the safety-relevant elements must remain functioning.
  - (ii) Safety-relevant components and equipment (gated spillways, bottom outlets) shall be fully operable after the OBE and therefore should behave elastically during the OBE.

- The following criteria apply for the SEE:
  - (i) Dam body and foundation: The reservoir must be retained safely, structural damage (cracks, deformations, leakage etc.) are accepted as long as the stability of the dam is ensured and no large quantities of water are released from the reservoir causing flooding in the downstream region of the dam.
  - (ii) After the SEE the reservoir level must be controlled and it must be possible to release a moderate flood by the spillway or low level outlet(s), which must remain functioning.
  - (iii) After the SEE it should be possible to lower the reservoir for repair of earthquake damage, and/or to increase the safety of a dam, if there are doubts about its static or seismic safety after an earthquake or other incidents.
  - (iv) Safety-relevant components and equipment (gated spillways, bottom outlets) must be fully operable after the SEE. Minor distortions and damage (e.g. leakage of seals of gates) are accepted as long as they have no impact on the proper

functioning of the components and equipment. This means that all gates, valves, motors, control units, power supply and emergency power generators for the spillway and low level outlets must withstand the SEE ground motions and they must be functioning after the SEE, i.e. the equipment shall be properly anchored etc. This is a new requirement of ICOLD (2016), which concerns hydro-mechanical and electro-mechanical engineers, who may not have been fully aware of their importance in the seismic safety of dams.

The OBE performance criteria can be verified by dynamic linear-elastic stress and deformation analyses - usually time history analyses -, and by rigid body sliding (and overturning) stability analyses using the peak acceleration acting in the centre of gravity of the sliding mass. The safety criteria are given in terms of allowable stresses, deformation (e.g. crack width) and allowable sliding stability safety factor for the OBE load combination. The safety criteria are basically the same as those used in pseudo-static analyses, however, the pseudo-static method has been replaced by a linear dynamic analysis, and the seismic coefficient has been replaced by the peak acceleration acting on the moving mass.

The SEE performance criteria for the dam body will require a nonlinear dynamic analysis as discussed in the subsequent Section. These analyses must all be done in the time domain, requiring the seismic input in the form of acceleration time histories. The main results required for the safety checks are the inelastic deformations of the dam after the earthquake. The basis of the safety checks are the failure modes of embankment and concrete dams as discussed below. The main structural failure modes can be checked based on dynamic stability analyses of slopes of embankment dams, sliding blocks of concrete dams or wedges in the dam abutments.

The main seismic failure modes of embankment dams are as follows (Wieland 2016):

- Overtopping of rockfill dam due to (i) malfunction or blockage of spillway gates (overtopping will occur after the earthquake), (ii) excessive seismic settlements of embankment dams, causing overtopping, or (iii) mass movements into the reservoir, causing impulse waves and overtopping of the dam crest.
- Internal erosion due to (i) insufficient protection of core of earth core rockfill dams, (ii) sliding movements of slopes or fault movements in the dam footprint that exceed the thickness of the fine sand filter, or (iii) damage of the contact between the core, abutment rock, concrete structures or conduits through the dam body (due to settlements, poor compaction etc.).

For concrete gravity dams and buttress dams the main seismic failure modes due to ground shaking are as follows:

- Sliding of concrete block along discontinuities in foundation rock or along the dam-foundation contact (sliding in downstream direction).
- Local sliding stability of concrete blocks near the dam crest (sliding in downstream direction along lift joints).

For concrete arch and arch-gravity dams the main failure modes due to ground shaking are:

- Global sliding of dam or different blocks along discontinuities in foundation rock or along the dam-foundation contact (sliding in downstream direction).

- Local sliding stability of concrete blocks near the dam crest (sliding in upstream direction along lift joint; due to the dam geometry, block sliding movements are larger for empty reservoir than for full reservoir).
- Crushing of concrete in thin arch dams under high seismic compressive stresses in arch direction (spalling of concrete and loss of bearing capacity in arch direction).

For other types of dams, other failure modes have to be considered. This applies mainly to earth dams, concrete face rockfill dams, asphalt core or asphalt surface dams, dams on soil foundation, dams on problematic foundations (dissolution of material, liquefaction, etc.).

For the seismic safety checks, time history analyses are required, which require the seismic input in form of acceleration time histories. These time histories are not physically correct earthquake records but models of the earthquake ground motion as discussed by Wieland (2018b). Using ground motion models will result in a safe dam design. It is important that this is also understood by earth scientists involved in seismic hazard studies for large dams.

3. LESSONS LEARNT FROM EARTHQUAKE DAMAGE OF DAMS

It is important to note that many dams, mainly small embankment dams, have been damaged by strong earthquakes such as, e.g. the 2008 Wenchuan earthquake in China, where some 2000 dams, reservoirs and hydropower plants were damaged or the 2001 Bhuj earthquake in India, where after the earthquake some 240 dams had to be strengthened. Also during the 1976 Tangshan earthquake in China, the 1991 Manjil earthquake in Iran, the 2010 Maule earthquake in Chile and the 2011 Tohoku earthquake in Japan, several dams were damaged. These are some recent examples, but dams were also damaged by other earthquakes elsewhere.

The important observation is that these dams were damaged despite the fact that they were designed against earthquakes using the pseudo-static analysis method, if they were designed against earthquakes at all. The damaged dams, designed with the pseudo-static method, should not have been damaged at all, as in the design the stresses and sliding safety factors were all satisfied. This is clear evidence that this method is not suitable for the seismic design and safety assessment of dams.

Observations of earthquake damage in concrete gravity dams show that ground shaking results in the formation of cracks in the highly stressed central crest region along some weak planes, such as horizontal lift surfaces and grouted vertical contraction joints (Wieland 2008b).

As no arch dam has so far suffered serious damage during earthquake ground shaking, little experience exists about the possible damage caused in an arch dam by, for example, the SEE. However, linear-elastic dynamic analyses show that tensile stresses exceeding the dynamic tensile strength of mass concrete could occur in an arch dam during a strong earthquake. Therefore, cracks can also be expected to develop in an arch dam during a strong earthquake along the contraction and lift joints, which exhibit a smaller tensile strength than the surrounding mass concrete.

The typical blockwise construction of a concrete dam, with horizontal lift joints at 2 to 3 m spacing, facilitates the formation of horizontal cracks during a strong earthquake. Most of the deformations of a dam would be confined to these cracks and therefore further cracking is prevented in the dam body. Thus, it can be expected that only a few cracks will be formed in a concrete dam during severe ground shaking.

4. DISCUSSION OF NONLINEAR SEISMIC ANALYSIS METHODS

4.1 Concrete dams

In order to predict the behaviour of a concrete dam during the SEE and to check the stability of a cracked dam, nonlinear seismic analyses would be required. The following approaches are presently used:

(i) the smeared crack approach, in which concrete cracking is implemented in the constitutive model of mass concrete (continuum approach); and

(ii) the discrete modelling of contraction, base and lift joints in the finite element model of the dam, assuming concrete and rock to be linear-elastic materials.

Based on the observation of the Sefid Rud dam in Iran, which has probably experienced the strongest ground shaking any concrete dam has experienced up to now and based on shaking table tests of large Chinese arch dams, it is concluded that only few cracks will develop in concrete dams, and therefore, the discrete crack model represents reality much better than the smeared crack approach, favored by many researchers. The post-cracking behavior of detached concrete blocks has been discussed by Malla and Wieland, 2003. Post-earthquake stability analyses should consider the uplift pressure acting on the sliding surface. The dynamic overturning stability is less of a problem, as the rocking motion of a detached concrete block is generally a reversible process, whereas sliding is a cumulative process.

Today, roller compacted concrete (RCC) dams are favored. Most of them are gravity dams and, therefore, their earthquake behaviour is also similar to that of conventional gravity dams.

4.2 Embankment Dams

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

- permanent (inelastic) deformations experienced during and after an earthquake;
- stability of slopes during and after the earthquake, and dynamic slope movements;
- build-up of excess pore water pressures in embankment and foundation materials (soil liquefaction);
- 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 face or asphalt membrane, geotextiles, grout curtain, diaphragm walls in foundation, etc.); and
- vulnerability of dam to internal erosion after formation of cracks or formation of loose material zones due to high shear.

Most of the above aspects are directly related to seismic deformations of the dam during strong ground shaking. Therefore, they are governed by the deformational characteristics of the fill materials. Moreover, the buildup of pore pressures in soils may cause liquefaction, which is a major problem for tailings dams and small earth dams constructed of or founded on relatively loose cohesionless materials.

For large storage dams, the earthquake-induced permanent deformations must be calculated. The calculations of the permanent settlements of large rockfill or concrete face rockfill dams based on dynamic analyses are still very approximate and are based on the linear-equivalent method with shear strain-dependent shear moduli and damping ratios, developed in the late 1960s. The permanent seismic deformations of dams cannot be calculated properly by this widely used method. This is a problem for dams with a thin waterproofing membrane, such as asphalt core rockfill dams, which are favored, today, by dam engineers.

5. SPECIAL ANALYSIS ASPECTS OF CONCRETE AND EMBANKMENT DAMS

For the dynamic analysis and seismic safety assessment of concrete and embankment dams, various features have to be considered, such as:

- two-dimensional or three-dimensional geometry of the dam-foundation model;
- dynamic dam-reservoir-foundation interaction effects;
- dynamic stability analyses of concrete blocks, slopes and abutment wedges;
- superposition of static and dynamic load cases;
- dynamic material properties of concrete, soil, rockfill and foundation rock;
- dynamic (tensile) strength properties of concrete, soil, rockfill and foundation rock;
- joints in concrete and rock;
- effect of uplift or pore pressure in joints;
- pore pressure buildup in soils;
- structural damping;
- stress concentrations in concrete dams and others.

Most of these features call for nonlinear analyses. As besides the seismic input there are large uncertainties involved in the dynamic material properties and since a number of assumptions have to be made in the different dynamic analyses, there is a need for sensitivity studies and the use for different analysis models and computer programs for verification purposes. Terefore, improvements in the computer programs for the nonlinear dynamic analysis of complex dam models does not actually improve the seismic safety of a dam.

6. NONLINEAR SEISMIC ANALYSIS OF DAMS

There exist several general-purpose computer programs (ABAQUS, ADINA, ANSYS, FLAC, Midas, etc.) that can be used for the nonlinear seismic analyses of concrete and embankment dams. A simplified nonlinear analysis method may still provide an equally safe seismic design of a dam as a sophisticated analysis as there are significant uncertainties in the seismic input and the material properties as discussed above.

The following stepwise approach towards nonlinear seismic analyses is recommended (direct time history analysis is required in all cases):

(i) Concrete dams:

- Linear-elastic dynamic analysis for OBE;
- Newmark-type sliding block analysis of whole gravity dam structure or detached blocks in a concrete dam;
- Rigid body analysis of cracked concrete (gravity, arch-gravity or arch) dam assuming that all deformations occur along cracks or joints, whereby cracks form along lift joints or the dam-foundation contact; and
- Analysis of arch-gravity and arch dams with contraction joint opening, or opening of dam-foundation contact.

A concrete damage model with tension failure criterion may be suitable for monolithic dams, but it does not account for reduced strength properties of contraction and lift joints and, therefore, may not be better than the simple models listed above.

(ii) Embankment dams:

- Equivalent linear dynamic analysis of dam; and
- Newmark sliding block analysis (simple method for estimating sliding movements of slopes).

Methods for nonlinear seismic analyses of embankment dams are still in the development phase. Progress has been very little in the last 50 years. The equivalent linear method is still the method used for most dam analyses. But methods are needed, which allow a more realistic analysis of dams with thin waterproofing membranes.

7. SUMMARY AND CONCLUSIONS

A thorough understanding of the inelastic and nonlinear seismic phenomena, which are expected during strong ground shaking, is the prerequisite for any nonlinear seismic analysis of dams. In a concrete dam, strong ground shaking could lead to opening of contraction joints and formation of horizontal cracks along lift joints. Similarly, an embankment dam may undergo significant permanent deformations during a severe earthquake. Some structural damage is accepted in a dam as long as the water retaining function is ensured. For the seismic safety and damage assessment of concrete and embankment dams, nonlinear dynamic analyses are often needed to determine the expected inelastic deformations under the safety evaluation earthquake ground motion.

Simple nonlinear analyses methods are still widely used for the seismic analysis of dams, such as the Newmark sliding block method and the equivalent linear method for the analysis of embankment dams, developed in the 1960s. In view of an increasing demand for nonlinear methods of analysis for the safety evaluation of existing and new dams according to the current seismic design criteria (ICOLD 2016).

The methods for nonlinear dynamic analysis of dams are still under development. These analyses have to be done in the time domain and need the seismic input in form of acceleration time histories; they need substantial engineering judgment.

The pseudo-static method and the use of seismic coefficients to represent the design earthquake ground motion is an outdated concept and shall no longer be used for large dam projects. The results of such analyses may be wrong. These facts have been known since the 1971 San Fernando earthquake in California. The characterization of the seismic hazard by a seismic coefficient is not based on scientific principles.

For the dynamic slope stability analysis residual strength properties shall be used and in the case of increased pore pressures, these must also be taken into account as they reduce the shear strength.

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