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LONG TERM BEHAVIOUR OF DAMS – EARTHQUAKE LOADING DESIGN

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Dams are built to serve for a long time of reliable and safe operation which is monitored for many dams since a long time period. In the course of time during the operation of those dams partly the design philosophy and construction methods have changed to cope with the state of the art. Especially when designing dams which are built abroad it is necessary to adapt the design prerequisites. It is of importance to reconsider under such circumstances loading conditions to minimize possible risks.
Dam ageing is describing the long term behaviour which might be interpreted as any change in dam properties with the passage of time and might affect dam safety. This ageing process includes the dam body together with the foundation, the grouting works and joints etc. This process is monitored with an adequate instrumentation and interpreted by the analyses of recorded data together with regular visual checks.
Within this contribution the long term behaviour of concrete dams together with the process of ageing is described with special regard to regulations devoted to earthquake adequate design. As example for the application of design regulations to safety assessment as part of the long term behaviour of dams a gravity and two arch dams are examined.

LONG TERM BEHAVIOR OF DAMS

Dams have a good durability and capacity to retain their operational requirements. Our experience is based on reported structural behaviour of dams and gained experience with dams involved in any kind of unforeseen behaviour. The dam ageing is interpreted as any change in dam properties with the passage of time if these changes affect dam safety.
The life span of a dam might be divided into periods of young, medium and old age. The first years - the so called ’young age’ - are characterized with irreversible deformations, high plastic deformations and lower material parameters (modulus of elasticity, compressive and tensile strength). For mass concrete the influence of hydration temperature with the increase of mechanical parameters is important during the first year. Due to the amount of creep present during the first years, stress concentrations are reduced in the dam and stress redistribution takes place.

Figure 1: Zillergruendl Arch Dam – constructed 1980 – 1985

During ’medium age’ the dams behaviour is characterized with a stable condition and repeatable (e.g. Austria) yearly, seasonal pattern. During the increase of age an improvement in the material parameters are to be recognized. This leads to an additional gain of overall structural safety.

The ’age old’ can be characterized with an increase of structural deterioration, with an impaired structural safety and a remaining life expectancy for several years.

Ageing of a dam is a process which includes the dam structure together with grouting works, joints etc. and the foundation. The ageing process is naturally monitored together with regular visual checks, adequate monitoring instrumentation and the analysis of recorded data.

However, due to changes in construction techniques, mechanization of construction and increase in knowledge together with an incorporation of quality control concept, the overall life time of a dam might be several times of the planned one.

Foundation

The development of rock mechanics and treatment of the foundation as an integral part of the overall bearing system has improved the situation. Whereas areas of uncertainties still exist due to a limited knowledge of rock characteristic along foundation, which is generally heterogeneous, inelastic, anisotropic and apparently with changing properties. The ageing process which modifies the rock behaviour can be classified in change of stress and increase of joints together with a change in seepage conditions. This process could be self stabilizing or needs certain external intervention, to prevent e.g. degradation of weak infillings.

Concrete

During the early decades of 20th Century the concrete technology was not properly established, with poor gradation and high water content. Due to these circumstances the results were porous concrete with low density and high permeability. The treatment of construction joints was not adequate.

Disregarding effects like crack formation at the abutment (matter of early age) and apart from chemical changes - due to alkali reaction or aggressive water - the increase of age is in general beneficiary for the overall dam safety. An increase in the elastic modulus leads to a reduction in elastic deformations. However creep effects (short and long term) need to be accounted for especially in arch dams. This effect leads to redistribution of stresses which are to be accounted for only with appropriate analysis tools. The effect of increased time dependent plastic deformation has to be considered, monitored and measures have to be taken.

A reported increase in the compressive and tensile strength of concrete leads to an increase in structural safety. A long term prediction of the evolution of material properties should be provided together with a continuous inspection process.

The degradation of concrete might be subdivided according to Brighton (1991) into:

- porous - permeable concrete, poor gradation
- freeze / thaw damage
- deteriorated leaking joints, construction joints
- erosion damage, reactive aggregates.

The effect of that behaviour has to be taken into consideration for each individual case which is considered and remedial measures to be carried out.

Reduction of Drain Efficiency - Grout Curtain Leakage

Both concrete and foundation drains should be kept in good operational condition in order not to impair the overall structural safety. On the other hand, the designer has to provide with appropriate design assumptions if drainage holes could be locked during the dams service time, without proper maintenance. This might especially be the case in foreign countries under uncertain conditions.

Especially together with the occurrence of tensile stresses at the upstream heel of the dam, the grout curtain may be deteriorated. Therefore provisions during the dam design (during a linear analysis approach - respectively in the foundation rock) and instrumentation have to be made to detect unintentional behaviour.

Monitoring - Instrumentation

The appropriate design of monitoring instrumentation must take into account the relevant parameters of load and behaviour of the structure. This leads to the extent and type of required measurement equipment for each dam on a case to case basis.
The measurement equipment is often the first element of a dam effected to ageing, which has to be taken into account by updating of the equipment. This will maintain the level of accepted standards for monitoring, corresponding analysis and interpretation.

Detection of Ageing

With the help of a regular monitoring and surveillance concept the process of ageing or any subsequent alteration in the regular behaviour should be detected. As a consequence to that, the decision about additional investigations to be carried out has to be made based on current state of the art.
To investigate alterations different steps are commonly used to investigate the current status of material properties:

- in situ test - geophysical measurements
- laboratory test.

Structural Integrity - Dynamic Property Investigation

For being able to investigate with numerical methods the earthquake behaviour as e.g. of a rockfill dam a seismic tomography was carried out to identify:

- the protective rockfill cover - riprap
- up- and downstream shoulder
- clay core and filter transition zones.

With the help of the compressive wave velocity distribution in the upstream shoulder of a dam the dynamic excitation is evaluated and the earthquake dam safety analyzed. The results revealed higher shear wave velocities than expected. These results are explained by consolidation settlements. This increase of dynamic properties detected by geophysical methods will result in a reduction of dynamic excitation to the dam crest.

Concrete Strength under Dynamic Loading

Under increased strain rate the tensile as well as the compressive strength of concrete increases. This is due to the heterogeneous kind of concrete and the inertia of propagation of micro cracks. Common strain rates for earthquakes are – according J. *Eibl (1999)* - in the range of $1*10^{1}$ to $5*10^{-3}$ s^{-1}. It is shown that the tensile strength for this strain rate increases by a factor of 1,5 to 2 compared to the strength determined under static conditions. For the same range of strain rate the increase in compressive strength is smaller and results to be about 1 to 1,5.

For an increase of strength by a factor of two for the tensile strength a strain rate of about 5 s^{-1} is sufficient whereas the compressive strength needs a ten times faster increase namely a strain rate of 50 s^{-1}.
To account for that effect a time-loading history dependent material law should be employed for a detailed investigation. This was for the examples studied herein not considered yet due to the local appearance of high stresses (singularities) only.

Conclusion - Ageing

The following conclusion on ageing of dams according to J. Combelles (1991) can be drawn:

- Efficient maintenance of the operator provides for retarded ageing
- Old Dams
  These are of special interest, because the engineering practice has changed during last decades (e.g. spillway, instrumentation). Safety assessment needs to be carried out every few decades and necessary adjustments have to be provided. The procedures for optimizing safety and economics have not always be found and are always to be ’negotiated’.
- Concrete dams are more vulnerable than embankment dams
- Different ageing mechanisms are to be mentioned in detail:
  Alkali aggregate reaction
  Foundation of large arch dams - cracking at dam heel
  Embankment dam cores - suffer hydraulic fracturing; risk of internal erosion.

For recently built dams it can be expected that the process of ageing will be retarded due to design measures and current construction methods. Despite of that a close cooperation between operator and designer will help to share the experience of common problems and how these can be prevented or overcome due to design or construction precautions.

Earthquake Appropriate Design

During the past - prior to about 1960 - earthquake loading in design regulations was approximately considered by assuming additional static loading without accounting for the dynamic nature of the excitation and the structural response. Since envisaged severe shaking of dams the earthquake loading was considered more rigorously and research work were initiated.
According to the state of the art and standard regulations the design of new dams is carried out. The state of the art is defined and reassessed during execution of projects, gaining of experience and with the help of recently gained research results. Standards are common accepted rules for work to be carried out paying attention to specific local needs. At the very beginning for the design of special important structures normally regulations are worked out comprising standards and state of the art developments. However, the decision about the design criteria is essential for the long term behaviour of

the dam structure. In that light the currently used design criteria were updated for earthquake analysis and are examined herein.
According to recommendations the following earthquake events are specified:

- MCE - Maximum Credible Earthquake, is the largest reasonably conceivable earthquake that appears; the probability of occurrence may vary from less than hundred to several thousands of years
- MDE - Maximum Design Earthquake, represents the maximum event, for which the dam should be designed for
- OBE - Operation Basis Earthquake, presents the ground motion under which the dam and appurtenant structures should remain functional and damage easily repairable.

Approach in Austria

An overview on the status of guidelines is given in *ZenzG,ObernhuberP., Aigner E. (1998)*.
The guidelines for seismic safety evaluation for dams cited have been established by a working group of the Austrian Commission on Dams. In general, guides of the Dam Commission are not classified as obligatory codes in a strict sense, but should be understood as recommendations to assist the experts and to promote consistent evaluation criteria. The guide for seismic safety evaluation applies to dams and reservoirs, river barrages as well as retention basins. The structures are not categorized into risk groups, however simplified evaluation procedures are intended for smaller dams. The evaluation of the seismic parameters follows the ICOLD recommendations. Therefore an Operating Basis Earthquake (OBE) and a Maximum Credible Earthquake (MCE) are considered.

- The seismic input is defined in terms of maximum horizontal acceleration and unified response spectra. Artificial acceleration time histories which are compatible with the response spectra are also provided and can be employed especially for non-linear analyses.
- The evaluation of the maximum horizontal acceleration is based on the earthquake-map using McGuire´s relationship between magnitude, distance and ground acceleration according *Lenhardt (1995)*. For the OBE, a return period of 200 years is selected. The resulting values are shown in a map over the country whereby a minimum value of 0.6 m/s^2 is prescribed. For the MCE, the global geology and long-term tectonic processes are also taken into account beside the results of extreme-value statistics in the evaluation. The resulting ground acceleration could be considered as approximate values only and more detailed studies including the local geological situation are necessary for a specific site.
- The maximum acceleration of the vertical excitation is defined as 2/3 of the respective maximum horizontal acceleration.

Analysis

The mathematical model of a dam should include, beside the dam itself, the reservoir and a sufficient portion of the foundation. The degree of acceptable simplification depends on the type and height of the dam. For most cases it is considered acceptable to account for the reservoir using the added mass concept and to consider the foundation as a finite and massless zone.

The recommended calculation procedure for linear problems is the modal analysis combined with the response spectrum method as well as the time integration method. More simplified methods should only be used for smaller dams. If nonlinearities occur or are to be expected, their influence on the overall response can be approximately estimated on the basis of the linear calculation. If the effects tend to be significant, a non-linear analysis is recommended.

Assessment of safety is based either on the comparison of maximum stresses and strains with the material strength or, if non-linear analyses are performed, on the status of deformation or damage during and after the earthquake event. The general requirement is that the dam has to pass an OBE without considerable damages and a MCE without loss of the impounding capacity. Assessment of safety under earthquake conditions not only concerns the dam itself, but also the reservoir slopes and the appurtenant structures as e.g. spillway and bottom outlet.

Long Term Safety Assessment

Within the subsequent examples examined the application of a response spectrum analysis with added mass approach for dam reservoir interaction is demonstrated. The foundation is normally assumed massless. In certain cases it is required to use a time acceleration history for excitation purpose to carry out direct time integration.

Design Consideration Gravity Dam

For the design of Birecik HPP a seismic risk assessment was carried out leading to design spectra and maximum acceleration under both OBE (0,8m/s^2) and MCE (1,6m/s^2) earthquake loading condition. For the gravity concrete dam sections (gravity dam, intake and spillway) detailed two dimensional finite element calculations with a frequency response spectrum analysis were carried out. To take horizontal clay infilled joints for earthquake excitation into consideration a nonlinear analysis with direct time integration was in addition carried out to investigate the amount of nonlinear displacement capability. For the spillway section a resulting maximum sliding deformation after MCE of 1,7mm and a base joint opening of 3,7mm at the heel of the dam is evaluated. These nonlinear deformations are judged to be within an acceptable range.

During these design steps it figured out the earthquake loading to be the determining design load case. However, based on these detailed linear and nonlinear investigations a simplified procedure was derived to account for the dynamic loading with a pseudo-dynamic spread sheet calculation for a faster evaluation of results varying with geological site conditions. It could be shown during the comparisons that the pseudo dynamic analysis resulted in about 15% lower overall safety factors, compared with direct time integration methods.

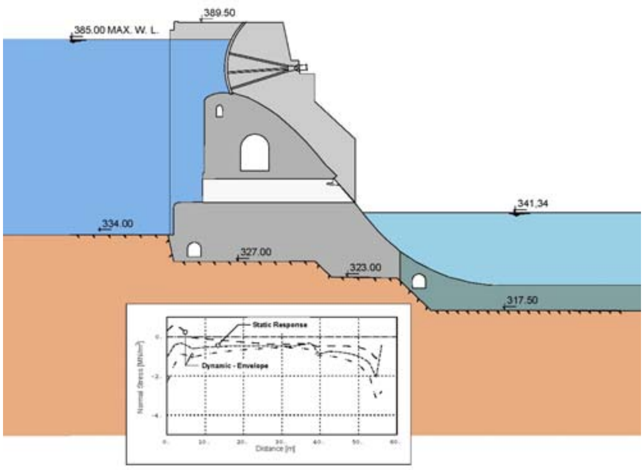

Figure 2: Gravity Dam Cross Section - Static and Dynamic Stress Distribution

Three Dimensional Arch Dam Analysis

The dynamic behaviour of Schlegeis arch dam was experimentally investigated during several research programs. The eigenfrequencies and modeshapes could be determined at different reservoir levels and under different ambient temperature conditions during the year. With the help of a numerical model (Figure 3) it was to evaluate the measured eigenvalues for comparison.
The calculation of eigenmode shapes were started with the static elastic deformation modulus. The interaction of the arch dam with the reservoir was accounted for with added mass approach and the foundation rock was incorporated with the static deformation values and is assumed massless. First results clearly indicated the necessity to increase the static modulus of elasticity for being able to get the dynamic system response as displayed.

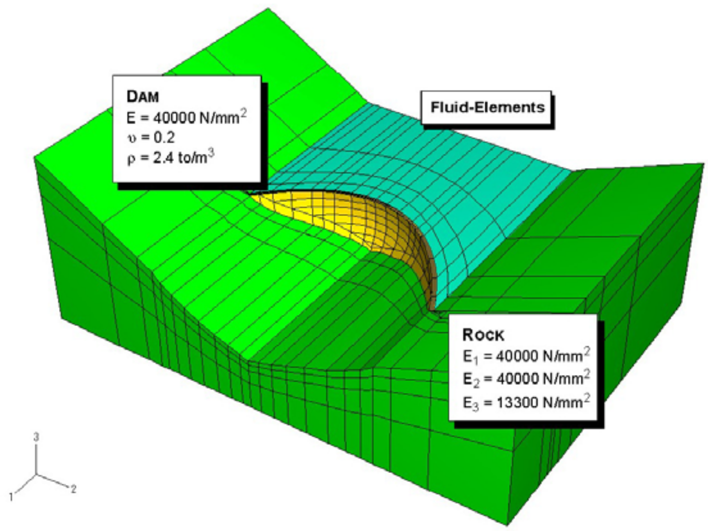

Figure 3: Schlegeis Dam - Finite Element Model

During the evaluation of the system response the added mass approach was verified by applying fluid elements to account for the reservoir with water filled. The dynamic structural system response is transformed by means of interface elements into a pressure distribution in the reservoir. At the reservoir borders a viscous boundary condition is used to prevent pressure wave reflections. For the first eigenmode the pressure distribution is displayed in [Figure 5].

Due to the fact that for one model, which of course is normally not the case, both results - namely added mass approach and fluid structure interaction - are calculated, the influence in the hoop stress distribution for the highest concrete column is displayed in [Figure 6]. As it can be seen clearly, the results evaluated with the added mass approach are at about 30% higher, than results evaluated with the more rigorous fluid structure interaction model. That shows in this case the results with added mass are more conservative.

With the help of these results the maximum dynamic stress distribution in the arch dam (Figure 4) and at the abutment is calculated. The evaluated results are compared with compressive and tensile strength. In general the system response due to OBE and MCE will be a linear one, except for few points at a small extent with stress concentrations. To investigate that specific point of interest a nonlinear analysis would be required. However, for the overall system performance during earthquake, these local effects are in this case of minor importance.

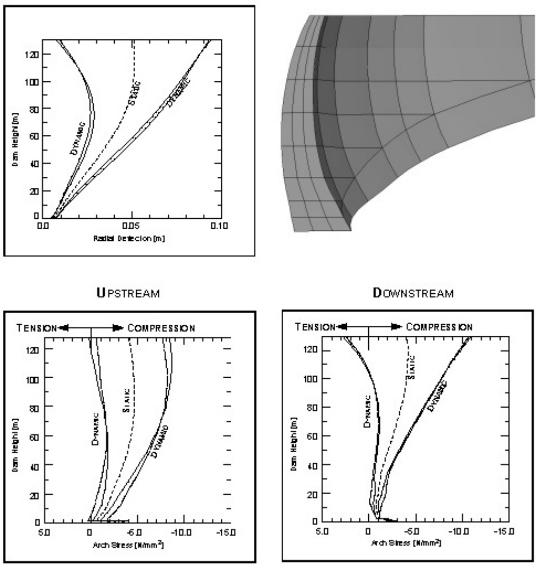

Figure 4: Schlegeis Dam – Resulting Stress Pattern due to Earthquake loading

Nonlinear Dynamic Arch Dam Analysis

Wiederschwing Dam, an about 30m high arch dam with a crest length of 73m, is taken as an example for the necessity to carry out a nonlinear seismic safety evaluation. The dam is located in Carinthia within an area with a relatively high seismicity. Starting from the normal operation for the OBE an acceleration of 8.6% of g (0,844 m/s^2) is applied. With these basic loading assumptions the linear response spectrum analysis is carried out.

The MCE loading has to be applied together with the normal operation condition. The maximum base ground acceleration is 22% of g (2,16 m/s^2). The linear dynamic earthquake analysis revealed high horizontal tensile stresses in the arch. Tensile stress won’t be transmitted across concrete block joints. Therefore, in addition to the linear analysis nonlinear calculations are performed to account for the block joint opening. The analysis is carried out by direct time integration method. The time history is generated with a special purpose program being able to approximate the frequency response spectra according to Austrian regulations.

The following assumptions are necessary prior discretization of the structure and carrying out the analysis as these are:

- dam reservoir interaction
- dam rock foundation energy radiation
- block joint behaviour and
- static structural loading condition.

The dam reservoir interaction is modelled by applying added masses according to Westergaard. This was found being justifiable and in that special case a conservative assumption. Within the evaluation of results the dam rock foundation interaction is approximated by massless elements discretizing the foundation rock. The finite element model of the dam is generated from as built drawings. The model with four relevant block joints is shown in figure 5. Within the analysis the block joints are intended to open under tension, are able to close again and are permitted to slide with a specified friction angle. The dynamic analysis is carried out under full water loading condition.

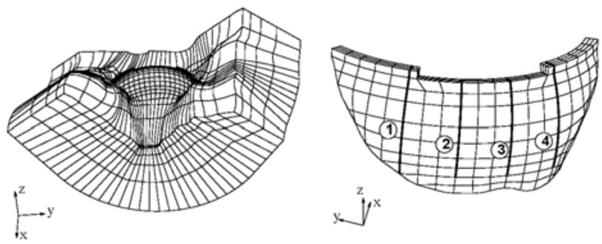

Figure 5: Finite Element Model – Nonlinear Block Joint Model

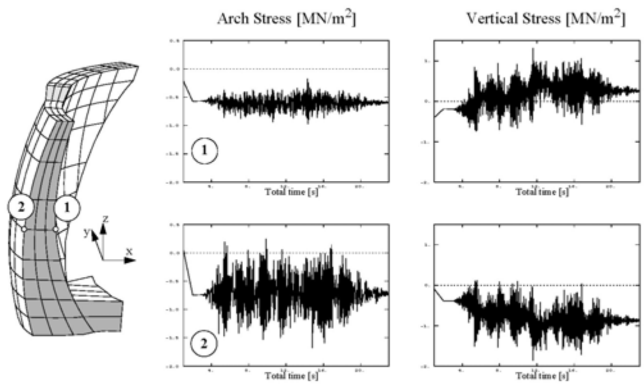

Figure 6: Stress Distribution at Upstream and Downstream Surface Nodes

Discussion of Results

Investigating the linear system response horizontal tensile stresses (hoop stresses) at the crest of 1,5MPa appear. The maximum compressive stress is at -3,1MPa. Considering the results from direct time integration with nonlinear block joint behaviour, we see a reduction of tensile stresses in y - direction from 1,5 to 0,8MPa at the dams upstream face but an increase of tensile stresses at dams downstream face. Additionally to that the

vertical stresses at the dams upstream face increase from about -1,0MPa to -2,3MPa and reaches at the downstream face tensile stresses at about 1,8MPa. This clearly shows the influence of cantilever bending moments in vertical direction due to opening of block joints.
During the nonlinear analysis the behaviour of the block joint is monitored in detail by means of the status of each surface node (open, closed, fixed, sliding) and the transmitted stresses. Some small opening of 0,5mm is traced as maximum. The so called sliding means relative displacement of nodes at the adjacent surfaces of a block joint. The resultant relative sliding deformation at the end of the MCE earthquake gives 2,5mm. The block joint stays closed after 20 seconds of shaking. Sliding with closed block joints is not significant at all during nonlinear analysis.
The nonlinear analysis is used to study the influence of block joint opening (due to high tensile stresses) on the stress distribution and amount of stress redistribution during earthquake in the arch dam. During the analysis it could clearly be studied, that the opening of block joints reduces the tensile stresses perpendicular to the joint surface to zero. This is monitored at the contact surface. The amount of maximum block joint opening is of about 0.6mm. At this ultimate deformation state 2/3 of the block joint opened.

Conclusions

Dams are designed for a long lasting time of safe and reliable operation. Apart from the design aspects and construction procedure the dam surveillance and maintenance throughout the service life plays a mandatory roll. The ageing and the performance of the dams are monitored being able to respond upon alterations.
As we can see from examples abroad and in Austria, design standards and regulations together with the so called ’state of the art’ are subjected to adaptation accord to experience and research results gained.
Though only a few examples of dam failure or serious deterioration due to earthquake are reported, this extreme loading case gathers a high focus of interest because of its disastrous consequences in case of occurrence. We do have a much better understanding upon the earthquake mechanism today and have refined design tools in our hand for current investigations. However, for existing dams it evolves - from time to time or occasionally - necessary to reassess the dam’s behaviour under normal and extreme loading conditions. Within this contribution the adaptation and application of design regulations for concrete gravity and arch dams are shown and examples are given.
We assume a service life time of dams of about one hundred year but - due to the design standards applied, construction methods used and careful dam maintenance exercised - we expect several hundred years for dams overall service life time.

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