17th International Benchmark Workshop on Numerical Analysis of Dams

09 – 12 April, 2025, Sofia, Bulgaria

Organized by:

ICOLD Committee A on Computational Aspects of Analysis and Design of Dams

Theme A

Three-dimensional Seismic Analysis of Tsankov Kamak Dam (double curvature concrete arch dam)

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Revision 0

Table with Revisions

Revision	Date	Comment
0	2024-06-28	Formulation document: first version

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1 Introduction

The stability of an arch dam and its foundation of rock mass is crucial for its performance during seismic activity. Dams are often located in seismic zones, so it is important to consider seismicity and seismic aspects during the design process, the dam operation and after decommissioning.

Since 1990, the Technical Committee A “Computational Aspects of Analysis and Design of Dams”, established within the International Commission on Large Dams (ICOLD), has organized International Benchmark Workshops (BWs) on Numerical Analysis of Dams.

The BWs aim to facilitate the sharing of knowledge and experience on numerical modelling in the areas of dam safety, planning, design, construction, operation, and maintenance.

The aim of the 2025 ICOLD BW Theme A is to continue and improve upon the work carried out in previous BWs focused on seismic analyses [1-4].

The most recent investigation on the topic was proposed in the Theme A of the 2019 ICOLD BW in Milan: “Seismic Analysis of Pine Flat Concrete Dam” [4]. The case study of the 2019 BW was a 2D structural problem: the simple geometry was specifically chosen with the objective to facilitate the adoption of complex and advanced methods and approaches to simulate the dynamic interaction of the dam with the reservoir and the foundation.

The case study proposed for the 17th BW in Sofia is the seismic analysis of Tsankov Kamak Dam, a concrete double curvature arch dam. To accurately define the response of concrete arch dams to earthquakes complex analyses, able to consider the three-dimensionality of the problem, the semi-unbounded size of the foundation, the non-linear behaviour of the system and the dynamic interactions of the dam with the foundation and the reservoir could be required. In the case of the 3D modelling of arch dams, the foundation cannot be idealized with a flat model (semi-unbounded half-space), but the presence of the canyon has to be conveniently taken into account.

The prerequisites for the 2025 ICOLD BW are important for the transition and upgrading of studies and investigations started at the 15th BW held in Milan.

2 Mission statement of this BW

The Theme A of the 2025 ICOLD BW refers to a simplified model of a double curvature concrete arch dam as a case study. The reference structure is "Tsankov Kamak" located in the south of Bulgaria, owned and maintained by the National Electric Company (NEK EAD).

Theme A deals with the three-dimensional seismic analysis of the dam-reservoir-foundation system.

The aim of the BW is to identify and determine findings and results to develop practices and methods for advanced analysis of concrete dams affected by seismic actions. The Contributors are free to choose their models, approaches and software which are expected to produce a wide range of findings and results that, however, do not serve for conclusions about the Tsankov Kamak dam safety.

Geometry of the structure, finite element model, material characteristics, static loadings (self-weight and hydrostatic pressure) and seismic input are defined by the Formulators and are common for all the Contributors.

Material properties are set linear-elastic for the concrete dam and the rock foundation in the mandatory case studies; non-linear properties will be provided to model the nonlinear behaviour of the dam in the additional (optional) analyses.

2.1 Roadmap

For Theme A analyses, all the Contributors are expected to use the same model geometry, material properties, and loads. To better achieve the objectives of the BW, the Formulators encourage the Contributors to study the results of the 2019 ICOLD BW [4].

Theme A is divided into 6 case studies (mandatory and optional tasks have been proposed, as later specified in Section 0):

- Case A – Static analysis
- Case B – Modal analysis
- Case C – Foundation dynamic analysis
- Case D – Linear dynamic analysis
- Case E – Non-linear dynamic analysis
- Case F – Linear dynamic analysis with massless foundation

2.2 Analysis Results

The results of the analyses should be submitted using the Analysis Results spreadsheets provided by the Formulators; results should be provided in International System of Units (SI).

The Contributors are in addition required to report their results descriptions, assumptions, used software, analysis methods, basic theory and models.

The Contributors will be expected to present their results during the BW. The organizers will provide a presentation template, and the Formulators will provide further details for the presentation.

The Formulators will gather, compare, evaluate and summarize the results for a comprehensive presentation at the BW aimed to identify general findings and correlations within the data sets.

2.3 General underlying assumptions and estimates

Theme A focuses on three-dimensional seismic analysis of a dam-reservoir-foundation system, which is an important aspect of safety dam operation. The theme is only addressed to assess the behaviour of the dam body, whereas the structural behaviour of the foundation is not an objective of this BW.

The mesh files of the dam with the foundation and the reservoir in various formats (.modfem, .neu, .inp, .ans) are provided by the Formulators. In order to simplify the calculations, the geometry, the water level and the material properties specified in this formulation may be different from the real ones used in the dam design.

Loads include self-weight, hydrostatic pressure and the seismic action, provided as acceleration time-histories in the three coordinate directions (upstream-downstream, cross-stream and vertical) and considered as a free field ground motion at the surface of the foundation.

2.4 Paper

The Contributors will prepare a summary paper documenting methods and approaches used in the study. The paper should describe the results based on the parameters specified in the problem formulation, as well as any other results obtained using optional parameters chosen by the Contributors for the investigation. Additionally, the paper should contain a discussion of the insights gained from the analyses, general observations about the model parameters that had the greatest impact on the results, and recommendations for further studies or research. The paper should adhere to the format provided in the accompanying file, '(Template)_Summary_Paper.docx', and be limited to 12 pages, including references. When submitting the summary paper, the Contributors are asked to use the file format '(Name)_Summary_Paper.docx'.

2.5 Benchmark Workshop presentation

During the BW session, the Formulators will describe the case studies and present a summary of the analysis results submitted by the Contributors. The Contributors will present their overall findings, investigated aspects, unexpected results in the analyses, or issues to address in the future. It is worth noting that the presentation of the case study should not be part of the contributor's presentations but only the analysis methods and results. The duration of presentations will be determined by the Formulators based on the number of the Contributors. Following the presentations, all BW Contributors and Participants will be engaged in an open discussion.

2.6 Time Schedule

The timeline of the 2025 BW workflow is the following:

- June 2024: detailed description of the Theme A by the Formulators on the BW website.

- July 2024: deadline to announce interest in the topic.
- September 2024: paper and presentation template and spreadsheets for results published on the BW website.
- December 2024: deadline for the Contributors to submit their results to the Formulators.
- February 2025: deadline to submit full paper for the BW.
- 30 March 2025: deadline to submit presentations for the BW.
- 09-12 April 2025: Benchmark Workshop in Sofia, Bulgaria.

3 General Information about Tsankov Kamak Dam

The Tsankov Kamak Dam, located in the Rhodope Mountains in the southwest of Bulgaria, is one of five projects in the Vacha River Cascade system.

The 130,50 m high dam has a double-curved arch shape and is situated in a wide valley, 400 m downstream from the confluence of the Vacha and Gashnya rivers. The reservoir formed by the dam has a total storage capacity of 111 million cubic meters.

The storage capacity available for use, between the maximum water level at elevation 685,00 m a.s.l. and the minimum operational capacity at elevation 670,00 m a.s.l., is 41 million cubic meters.

The civil works began in June 2004. During the initial two-year construction phase, road works, tunnelling and excavation for the main dam were primarily carried out. Construction of the main dam started in October 2007.

The reservoir impoundment began in July 2010 and the initial operation started in December of the same year. By the end of June 2011, the dam completed its initial operation phase and began regular operation.

3.1 Dam body

The horizontal arches of the dam are of constant thickness and parabolic shape. The arch is made of 23 blocks, 20 m wide each: 17 of these blocks form the arch in the middle part. The arch wall is supported by blocks on both slope sides. The left support block has a length of 38,23 m and the right one has a length of 46,11 m.

The joints between the blocks, formed along the tangent to the crown axis of the wall, were grouted after the blocks were completed.

The joints between the vertical blocks are formed with a series of 10-cm-thick shear key locks on both surfaces of each cantilever block. This ensures uniformly distributed shear force transmission between the blocks.

The dam's crest features four spillways blocks with segmental gates, symmetrically arranged with respect to the arch, as well as a spillway plunge pull in downstream heel. The bottom outlet of the dam is situated in the central block of the wall.

The main parameters of the dam are:

▪ Dam crest elevation:	el. 688,50 m a.s.l.
▪ Length of dam crest (arch)	340,0 m
▪ Total length of dam crest	468,0 m
▪ Lower elevation foundation	el. 558,00 m a.s.l.
▪ Max. dam height above foundation	130,5 m
▪ Centre block thickness at dam crest	8,79 m
▪ Centre block thickness at dam foundation	26,36 m
▪ Total volume of the wall	about 400 000 m^3
▪ Spillway single span width	8,0 m
▪ Spillways spans	4
▪ Elevation spillway	el. 679,50 m a.s.l.

- Elevation segment/ radial gates top el. 685,50 m a.s.l.
- Maximal operation water level el. 685,00 m a.s.l.
- Minimal operation water level el. 670,00 m a.s.l.
- Maximal water level el. 687,42 m a.s.l.

The general layout and the central block cross section of the of Tsankov Kamak Dam are reported in and in Fig. 1 and Fig. 2 respectively.

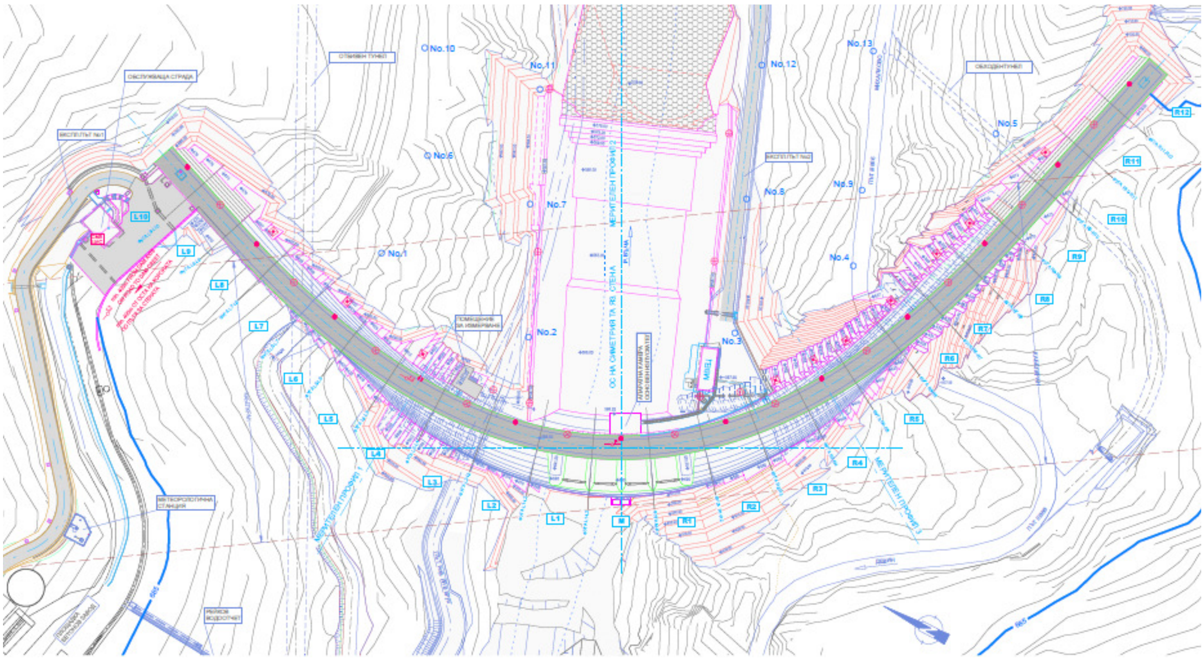

Fig. 1. General layout of Tsankov Kamak Dam

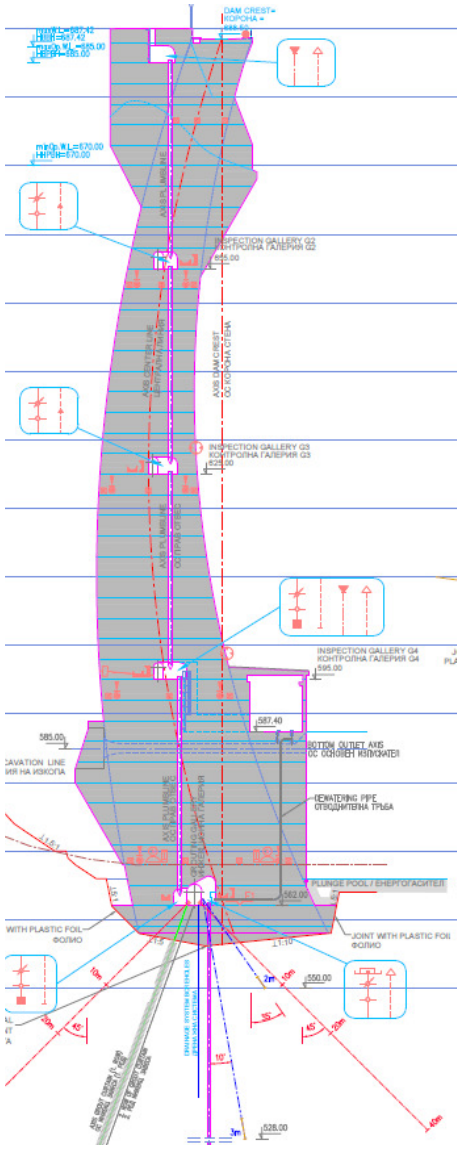

Fig. 2. Central block cross section of Tsankov Kamak Dam, with spillway, bottom outlet gate house and plunge pool integrated into the dam body

3.2 Geological conditions

The Tsankov Kamak Dam is located within the metamorphic complex made up of biotite gneisses and amphibole biotite gneisses, which are stratigraphically attributed to the Vacha Motley suite.

The Vacha Valley features high rock slopes with subpar geological conditions. In natural conditions, the geology in the area was considered to be in a pre-existing equilibrium state. However, excavation, dam construction, and reservoir impoundment can cause the rock structure to deviate from this equilibrium state.

The foundation is generalized by seven types of rock. Their elastic modules vary from 12 000 to 72 000 MPa, and Poisson's ratio varies between 0,24 and 0,27.

4 Case study description

The input data for Theme A, including dimensions and forces, are provided in the International System of Units (SI). Contributors may use any unit system in their analysis, but all results must be submitted in the SI. The units used in this context are kilograms (kg), meters (m), newtons (N) or meganewtons (MN), pascals (Pa) or megapascals (MPa), and seconds (s). It is assumed that the standard value for gravity, equal to 9,80665 m/s², is applicable.

4.1 Numerical FE model

The Formulators have developed a finite element model, which is provided to the Contributors of the benchmark workshop (Fig. 3, Fig. 4 and Fig. 5). The model consists of the following parts: the concrete arch dam, the foundation and the reservoir. A simplified model of the dam is considered, in which the spillway is simply represented by a hollow and the bottom outlet and the abutments are disregarded. The reservoir has been obtained by extruding the upstream face of the dam mesh for a length three times the total height of the dam: the resulting mesh is only joined to the upstream dam face, not to the rock. The domain of the foundation is 700 m long and wide and 400 m thick: this model is definitely adequate for the analysis with the massless approach, but the Contributors are invited to build the foundation model best suited to the adopted soil-structure interaction approach.

The dam has been meshed with eight-node iso-parametric solid brick elements, with a typical length of about 4 m. The dam consists of 11 375 nodes and 8 720 elements.

The reservoir has been meshed with eight-node iso-parametric brick elements (that can be transformed into acoustic or fluid elements depending on the adopted fluid-structure interaction). The reservoir consists of 21 989 nodes and 19 100 elements

The foundation has been meshed with eight-node iso-parametric solid brick elements. The foundation consists of 85 183 nodes and 77 952 elements. For the Cases in which the wave propagation in the foundation is required, the Contributors are encouraged to build the most appropriate foundation mesh for the approach adopted to deal with the dam-foundation interaction.

The mesh does not include the vertical joints and the dam-foundation interface: the modelling of the interfaces is left up to the Contributors according to the formulation available in the software used for the analyses.

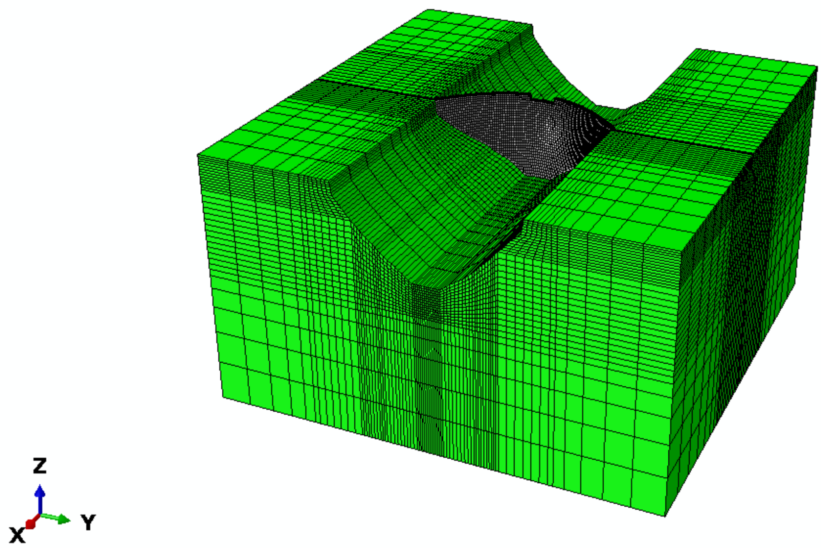

Fig. 3. Numerical model: dam and foundation, view from downstream

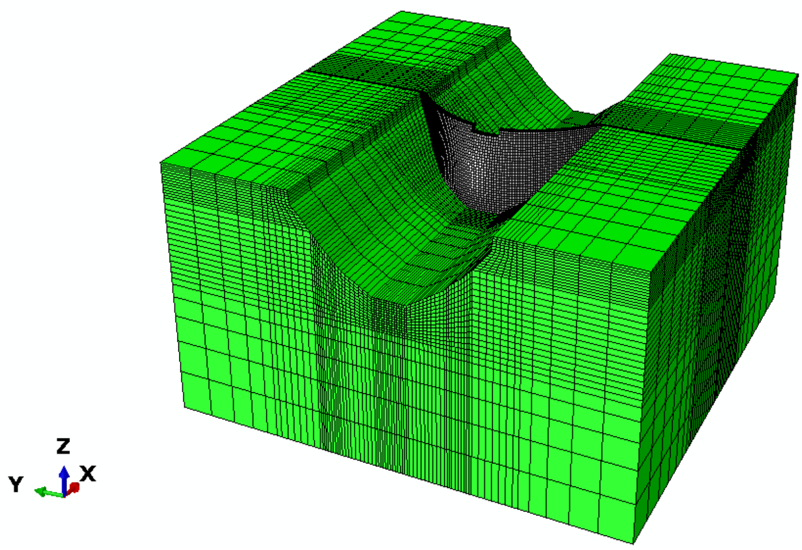

Fig. 4. Numerical model: dam and foundation, view from upstream

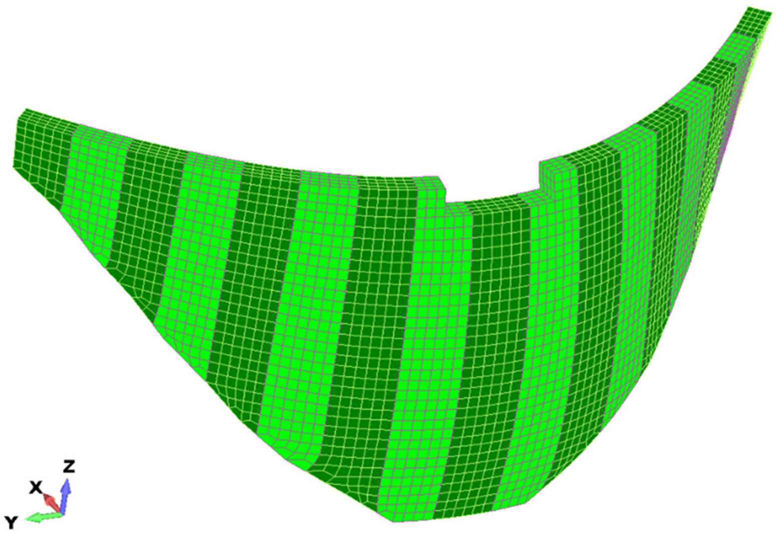

Fig. 5. Numerical model: dam, view from upstream

The mesh is available in various file formats that can be imported into most existing finite element codes.

- Femap: *.modfem
- Neutral: *.neu
- Abaqus input: *.inp
- Ansys input: *.ans

4.2 Material parameters

4.2.1 Dam concrete

For BW purpose, concrete is assumed to be homogeneous and isotropic, with the following properties.

▪ Density [kg/m^3]	2370
▪ Poisson's ratio (static/dynamic) [-]	0,2
▪ Static Elastic Modulus [Pa]	28x10^9
▪ Dynamic Elastic Modulus [Pa]	34x10^9
▪ Thermal expansion coefficient [-]	0,00001
▪ Compressive Strength, Cube [Pa]	25 x10^6
▪ Tensile strength [Pa]	2,4 x10^6
▪ Compressive strain at peak load [-]	0,0025
▪ Tensile strain at peak load [-]	0,00012
▪ Static Fracture energy [N/m]	310
▪ Dynamic Fracture energy [N/m]	400

Under dynamic loads, it is recommended that the tensile strength of concrete be 50% higher than under static loads. If this assumption is not met, the Contributors must provide an explanation for the different choice and its influence on the results.

Concrete compressive strength should be increased by 15% for dynamic loads compared to static conditions.

Rayleigh damping with a ratio of 5% is employed for the concrete material within the frequency range of interest.

4.2.2 Interfaces

For BW purpose, the vertical joints should be able to represent the non-linear effects due to their opening/closing. The stiffness parameters have to be defined by the Contributors.

The dam-foundation interface should be able to represent the non-linear effects due to their opening/closing and sliding. Ideally, it should follow a Mohr-Coulomb friction no tension constitutive law with the following properties:

- Cohesion [Pa] $1{,}5 \times 10^6$
- Friction angle [°] 60

The stiffness parameters have to be defined by the Contributors.

4.2.3 Foundation rock

For BW purpose, rock is assumed to be homogeneous and isotropic, with the following properties.

- Density [kg/m^3] 2675
- Poisson's ratio, static [-] 0,27
- Poisson's ratio, dynamic [-] 0,29
- Static Young/ Elastic Modulus [Pa] 28×10^9
- Dynamic Elastic Modulus [Pa] 34×10^9
- Shear Wave Velocity [m/s] 2220
- Compressional Wave Velocity [m/s] 4081

For BW purpose, the rock foundation is assumed undamped.

4.2.4 Water

Water is considered to have a unit weight of 1000 kg/m^3 and compression wave velocity of 1439 m/s.

4.3 Loads

The loads presented here are intended for various analysis cases.

4.3.1 Static loads

The static loads include the self-weight of the concrete dam (the self-weight of foundation should not be included) and the hydrostatic pressure of the water in the reservoir.

The reservoir water level is considered at the annual average WL of 679,00 m a.s.l..

The hydrostatic pressure is determined by the expected average annual water level. It is applied as an element pressure, normal to the outer face of all upstream dam elements under the assumed water level.

4.3.2 Seismic input

The input for the seismic analyses is defined by the three-component recorded accelerogram of a recent Bulgarian earthquake [5]. The maximum recorded acceleration, a_{max}, was scaled up to 0,25 g which, according to the results of the seismic hazard analysis performed in 2006 for the dam site, corresponds to a probability of exceedance of 0,001 with 85% probability. The input for the vertical direction was scaled by the same factor of the horizontal components.

The acceleration time histories in the upstream-downstream, cross-stream and vertical directions [5], showed in Fig. 8, Fig. 7 and Fig. 8 respectively, are provided in the file “Accelerograms.xlsx”.

The three-component acceleration time history is assumed to represent ground motion at the free surface, i.e., the motion that would be observed at the top of the foundation in the absence of the dam and reservoir (at the dam crest level).

Because free-surface motions are appropriate for input to models with a massless foundation, this acceleration record will be used for input to Case F. In contrast, free-surface motions typically are deconvolved at the base of the foundation for input to models using a foundation with mass. The deconvolution process is left to the Contributors.

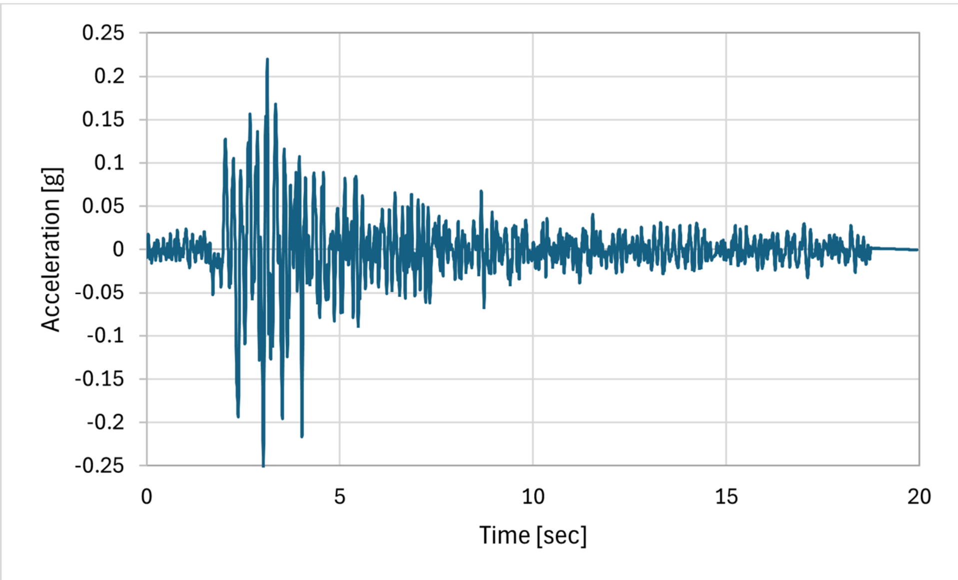

Fig. 6. Recorded accelerogram, scaled to represent an earthquake of exceedance of 0,001 with 85% probability: upstream-downstream component

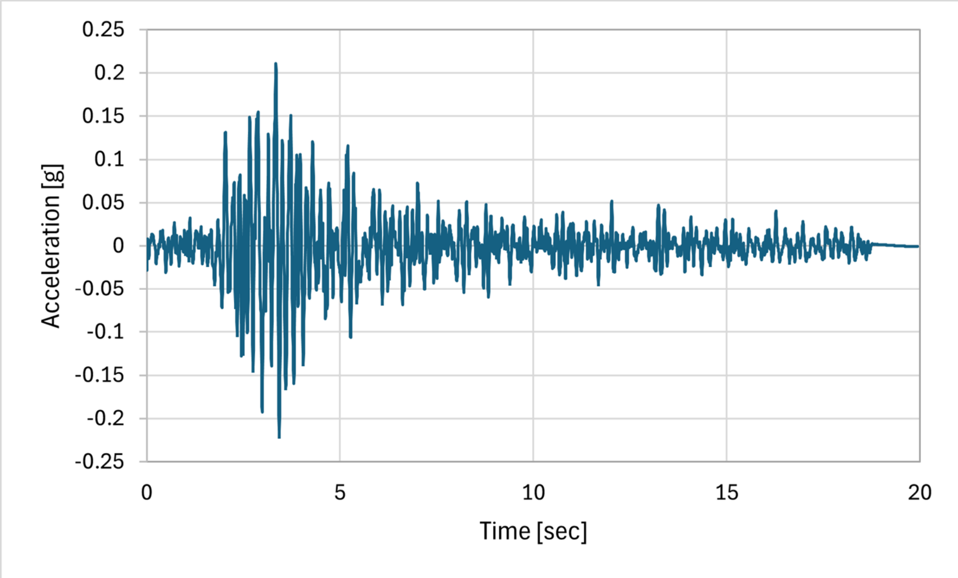

Fig. 7. Recorded accelerogram, scaled to represent an earthquake of exceedance of 0,001 with 85% probability: cross-stream component

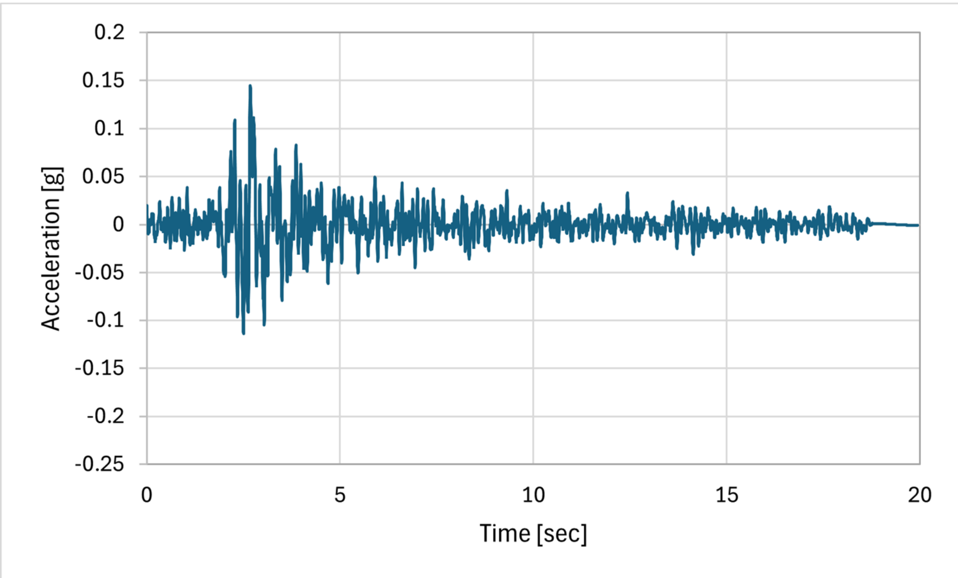

Fig. 8. Recorded three-component accelerogram, scaled to represent an earthquake of exceedance of 0,001 with 85% probability: vertical component.

The Contributors are free to choose the method for modelling the dynamic dam-foundation and dam-reservoir interactions, provided that the mass of the foundation and the compressibility of water are considered.

4.3.3 Initial condition for seismic analysis

The subsequent application of self-weight and hydrostatic pressure leads to the stress-strain state of the dam, which is used as the initial condition for the seismic analysis.

5 Case studies and tasks

5.1 Objectives of Theme A

The theme is divided into six cases (mandatory and optional), according to the type of analysis.

5.1.1 Case A – Static analysis

Case A deals with the static analysis of the dam-reservoir foundation system. The static loads are the self-weight of the dam and the hydrostatic pressure. Three separate model cases are proposed, gradually introducing nonlinearities. The constitutive law relevant to interfaces should be able to allow the opening/closing of the interfaces and also the sliding in the case of the dam-foundation interface. The constitutive law relevant to concrete should be able to represent its cracking behaviour. The Contributors should select the non-linear material constitutive models for interfaces and concrete and define all the parameters needed for the material model based on the provided information. Any material model parameters not provided by the Formulators should be chosen by the Contributors based on the current practice and engineering judgment.

Three model cases are proposed for static analysis:

- A-1 (mandatory). Monolithic linear analysis: considering the dam attached to the foundation and the elastic properties for the dam concrete specified in Section 4.2.1;
- A-2 (optional). Non-linear analysis (interfaces only): considering the vertical joints and the dam-foundation interface (with properties specified in Section 4.2.2) and the elastic properties for the dam concrete specified in Section 4.2.1;
- A-3 (optional). Non-linear analysis (interfaces and dam concrete): considering the vertical joints and the dam-foundation interface (with properties specified in Section 4.2.2) and the non-linear properties for dam concrete specified in Section 4.2.1.

For analysis consistencies, the Contributors have to consider the following input parameters and assumptions:

- foundation elastic properties in Section 4.2.3;
- water properties in Section 4.2.4;
- static weight of the dam but not of the foundation;
- hydrostatic pressure at the annual average WL of 679,00 m a.s.l.;
- boundary conditions defined and justified by the Contributors as appropriate for static analysis.

The following results are required:

- radial displacement of the upstream face for the centreline of the central block vs. elevation;
- vertical and hoop stresses of the upstream and downstream faces for the centreline of the central block vs. elevation;
- contour plots of maximum and minimum principal stresses;

- contour plots of joint opening (for model Case A2 and model Case A3);
- contour plots of the Damage Index (DI) or other method depending on the constitutive model and the software used (for model Case A3 only).

5.1.2 Case B – Modal Analysis

Case B consists in the modal analysis of the dam-reservoir-foundation system.

The modal analysis should be performed for two model cases:

- B-1 (mandatory): foundation with mass.
- B-2 (optional): massless foundation.

For analysis consistencies, please consider the following input parameters and assumptions:

- the dam is considered attached to the foundation;
- concrete elastic properties in Section 4.2.1;
- foundation elastic properties in Section 4.2.3;
- water properties in Section 4.2.4;
- the mass of the dam, the reservoir and the foundation (for model Case B1 only);
- water level at the annual average WL of 679,00 m a.s.l..

The following results are required:

- the first 15 natural frequencies (eigenfrequencies) of the dam-reservoir-foundation system;
- the corresponding 15 effective participation mass percentage in the upstream-downstream, cross-stream and vertical directions;
- the corresponding dam mode shapes for the first 5 natural frequencies.

5.1.3 Case C - Foundation dynamic analysis (mandatory)

The aim of Case C is to verify that, in free field conditions (i.e., neglecting the dam and the reservoir), the assigned seismic motion is correctly reproduced at a control point at the free surface (placed halfway between the dam right abutment and the right boundary of the foundation). A linear elastic dynamic analysis of the foundation without the dam and the reservoir is required for the seismic input specified in Section 4.3.2. This is a wave propagation analysis only: static analysis due to weight of the foundation material (gravity loads) should not be included.

For analysis consistencies, please consider the following input parameters and assumptions:

- foundation elastic properties in Section 4.2.3;
- mass of the foundation;
- boundary conditions defined and justified by the Contributors as appropriate for dynamic (wave propagation) analysis (compliant or non-reflecting, free-field);
- 0% viscous damping;
- seismic input specified in Section 4.3.2, given as a free field ground motions at the at the free surface of the foundation;
- time histories in the upstream-downstream, cross-stream and vertical directions should be applied simultaneously.

The following results are required:

- acceleration time history in the upstream-downstream, cross-stream and vertical direction resulting from the foundation analysis at a control point at the free surface (placed halfway between the dam right abutment and the right boundary of the foundation).

5.1.4 Case D – Linear dynamic Analysis (mandatory)

In Case D the Contributors are required to perform the dynamic analysis of the dam-foundation-reservoir system, taking into account linear elastic material properties for the dam and the foundation.

For analysis consistencies, the Contributors have to consider the following input parameters and assumptions:

- the dam is considered attached to the foundation;
- concrete elastic properties in Section 4.2.1;
- foundation elastic properties in Section 4.2.3;
- water properties in Section 4.2.4;
- static weight of the dam but not of the foundation;
- hydrostatic pressure considering the water level at the annual average WL of 679,00 m a.s.l.;
- a dam-reservoir interaction model able to account for water compressibility is encouraged;
- mass of the dam, of the reservoir and of the foundation;
- 5% viscous damping for the dam and 0% for the foundation;
- boundary conditions defined and justified by the Contributors as appropriate for dynamic (wave propagation) analysis (compliant or non-reflecting free-field);
- the seismic input specified in Section 4.3.2, given as a free field ground motions at the surface of the foundation;
- time histories in the upstream-downstream, cross-stream and vertical directions should be applied simultaneously.

The following results are required:

- acceleration time history in the upstream-downstream, cross-stream and vertical directions at the crest of the central block;
- dynamic displacement (relative to the free-field) time history in the upstream-downstream, cross-stream and vertical directions at the crest of the central block;
- minimum and maximum radial dynamic displacement (relative to the free-field) envelopes of the upstream face for the centreline of the central block vs. elevation;
- vertical and hoop stress envelopes of the upstream and downstream faces for the centreline of the central block vs. elevation;
- the contour plot of the envelope of maximum and minimum principal stresses.

5.1.5 Case E - Non-linear dynamic analysis (optional)

Case E is equal to Case D except for the nonlinearity of interfaces (vertical joints and dam-foundation interface) and of concrete dam, gradually introduced by mean of two separate model cases: the Contributors are required to perform the dynamic analysis of the dam-foundation-reservoir system, taking into account non-linear material properties for interfaces and concrete dam. The constitutive law relevant to interfaces should be able to allow the opening/closing of the interfaces and also the sliding in the case of the dam-foundation interface. The constitutive law relevant to concrete should be able to represent its cracking behaviour. The Contributors should select the non-linear material constitutive models for interfaces and concrete and define all the parameters needed for the material model based on the provided information. Any material model parameters not provided by the Formulators should be chosen by the contributors based on the current practice and engineering judgment.

The non-linear dynamic analysis should be performed for two model cases:

- E-1 (optional): non-linear analysis (interfaces only): considering the vertical joints and the dam-foundation interface (with properties specified in Section 4.2.2) and the elastic properties for the dam concrete specified in Section 4.2.1;
- E-2 (optional): non-linear analysis (interfaces and dam concrete) (with properties specified in Section 4.2.2): considering the vertical joints and the dam-foundation interface and the non-linear properties for the dam concrete specified in Section 4.2.1.

For analysis consistencies, the Contributors have to consider the following input parameters and assumptions:

- foundation elastic properties in Section 4.2.3;
- water properties in Section 4.2.4;
- static weight of the dam but not of the foundation;
- hydrostatic pressure considering the water level at annual average WL at 679,00 m a.s.l.;
- a dam-reservoir interaction model able to account for water compressibility is encouraged;
- mass of the dam, of the reservoir and of the foundation;
- 5% viscous damping for the dam and 0% for the foundation;
- boundary conditions defined and justified by the Contributors as appropriate for dynamic (wave propagation) analysis (compliant or non-reflecting, free-field);
- the seismic input specified in Section 4.3.2, given as a free field ground motion at the surface of the foundation;
- time histories in the upstream-downstream, cross-stream and vertical directions should be applied simultaneously.

The following results are required:

- acceleration time history in the upstream-downstream, cross-stream and vertical directions at the crest of the central block;

- dynamic displacement (relative to the free-field) time history in the upstream-downstream, cross-stream and vertical directions at the crest of the central block
- minimum and maximum radial dynamic displacement (relative to the free-field) envelopes of the upstream face for the centreline of the central block vs. elevation;
- vertical and hoop stress envelopes of the upstream and downstream face for the centreline of the central block vs. elevation (for model Case E1 only);
- contour plot of the Damage Index (DI) or other method depending on the constitutive model and the software used (for model Case E2 only);
- contour plots of joint opening.

5.1.6 Case F – Linear dynamic analysis with massless foundation (optional)

Case F is equal to the Case D, except massless foundation is considered: the Contributors are required to perform the dynamic analysis of the dam-foundation-reservoir system, taking into account linear elastic material properties for the dam and the foundation. To enhance the comparison between massless approach and wave propagation models the same damping is required also in this case.

For analysis consistencies, please consider the following input parameters and assumptions:

- the dam is considered attached to the foundation;
- concrete elastic properties in Section 4.2.1;
- foundation elastic properties in Section 4.2.3;
- water properties in Section 4.2.4;
- static weight of the dam and reservoir but not of the foundation;
- hydrostatic pressure at annual average WL of 679,00 m a.s.l.;
- a dam-reservoir interaction model able to account for water compressibility is encouraged;
- mass of the dam and of the reservoir but massless foundation;
- 5% viscous damping for the dam and 0% for the foundation;
- boundary conditions defined and justified by the Contributors as appropriate for dynamic (massless) analysis;
- seismic input specified in Section 4.3.2, given as a free field ground motion at the surface of the foundation;
- time histories in the upstream-downstream, cross-stream and vertical directions should be applied simultaneously.

The following results are required:

- acceleration time history in the upstream-downstream, cross-stream and vertical directions at the crest of the central block;
- dynamic displacement (relative to the free-field) time history in the upstream-downstream, cross-stream and vertical directions at the crest of the central block;

- minimum and maximum radial dynamic displacement envelopes of the upstream face for the centreline of the central block vs. elevation;
- vertical and hoop stress envelopes of the upstream and downstream faces for the centreline of the central block vs. elevation;
- the contour plot of the envelope of maximum and minimum principal stresses.

5.2 Timeline (Estimated time needed to solve this topic)

It is estimated that the mandatory tasks will require between 20 to 30 working days to complete. Furthermore, the Contributors will have to allocate extra time for preparing their benchmark workshop article and presentation.

6 References

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