16th International Benchmark Workshop on Numerical Analysis of Dams

5 – 7 April, 2022, Ljubljana, Slovenia

Organized by

ICOLD Committee on Computational Aspects of Analysis and Design of Dams

Theme A

Behaviour prediction of a concrete arch dam

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Revision history

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2021-07-31	First version of the formulation document distributed to the participants

Contents

1 Introduction

Dam monitoring is an important part of the dam safety work to obtain greater understanding of the dam and is essential to identify changes in its behaviour that can occur during their service life. Proper assessment of the aging dams increases the knowledge of their current safety and allows for better planning of renovation and rebuilding investments.

Prediction of measurements and interpretation of future dam behaviour, based on the data gained with measurements, can therefore be considered as a common task for dam engineers nowadays. Previous research has shown that the behaviour of concrete dams is, to a great extent, governed by the ambient variation in temperature and water level. Thereby, utilizing different type of behaviour models that can account for these variations in ambient conditions has great potential to capture the expected response of a dam.

Moreover, these behaviour models are often a crucial part of dam safety systems. With the help of various prediction models, engineers can evaluate the dam's performance, estimate the response of the dam for its actual load conditions and define warning levels. Over the recent years, a vast development has occurred in the field of prediction models, especially regarding data-based and machine learning approaches. In addition to data-based models, numerical models based on the finite element method (FEM), are widely used to estimate displacements, stresses, and strains of the dam and therefore predict the dam response. These models are based on the physical laws that govern the processes. Due to the increased computer power, both data-based and numerical models gained in their level of detail and accuracy but also in their complexity. Both are used by dam specialists, and it is therefore important to study the capabilities of these methodologies for assessing the dam behaviour and predict the expected future behaviour of the dam.

The Technical Committee A "*Computational Aspects of Analysis and Design of Dams*" within International Commission of Large Dams (ICOLD) has organized international Benchmark Workshops (BW) on the topic of numerical analysis of dams since 1990. The purpose of these is to share knowledge and experience regarding numerical modelling within the fields of dam safety, planning, design, construction as well as operation and maintenance of dams.

In the 6th ICOLD BW in 2001, interpretation of the measurements at the Schlegeis dam was one theme at the workshop. Years later, in 2017, at the 14th ICOLD BW, a theme was focused on predicting the dam behavior, including cracking, caused by seasonal temperature variations. The aim of the current theme for the 2022 ICOLD BW is to build from the experience of past workshops and see how modern tools can be used in the prediction of dam behavior.

1.1 Focus of this benchmark problem

In this benchmark problem, denoted as Theme A in the 2022 ICOLD BW, a double curvature arch dam, located in the south of France and owned by the EDF (Électricité de France) is used as a case study. The name of the dam will remain undisclosed. The aim of the theme is to establish a prediction model for the dam. For this task, all types of models are welcome to use (statistical, hybrid, deterministic, machine learning, finite element modelling) from the simplest to the most complex ones.

The geometry, material properties, and the loads have been defined and are delivered by the formulators. The participants are given the monitoring data from the dam for the period 2000-2012. The provided data has been pre-processed and can be directly used for the analysis, e.g. no further cleaning is necessary. Furthermore, the data is provided without any modification of the actual time series and is measured with different frequencies. The participants are asked to build a model, calibrate it, and use it for long-term and short-term predictions using the provided data and by making their assumptions and choose suitable approaches to solve the problem.

Theme A consists of mandatory and optional tasks that are divided among three cases: calibration (Case A), short-term predictions (Case B), and long-term predictions (Case C). For the participants, it is mandatory to consider the radial displacement from two pendulums, evaluate them and provide results for all three cases. Other variables (crack opening, piezometric level, and seepage) are provided as well, while interpretation and prediction of them are optional.

1.2 Deliverables

All participants are requested to deliver their solution to the defined problem including output data, description of modelling assumptions, used software, etc. The theme is divided into both mandatory and optional tasks. For the mandatory tasks, the participants are asked to provide both predictions and warning levels for the monitored phenomenon.

In addition to delivering the requested results, each participant should provide an article describing the problem and the chosen solution methods. The organizers of the ICOLD Benchmark Workshop will provide a template for the paper.

All results will be collected by the formulators and compared at the Benchmark Workshop in Ljubljana, Slovenia, April 2022.

The participants will be asked to present their results during the Workshop. The organizers will provide a presentation template, while the formulators will provide additional information on the content of the presentation. The participants will be asked to present only the content relevant to their solution, while general introduction of the theme A will be presented by the formulators.

1.3 General basic assumptions

The focus of the theme is on the following variables:

- Radial displacement (two pendulums in the central block of the dam);
- Crack opening displacement (sensor at the rock-concrete interface);
- Piezometric levels (vibrating wire piezometers at the rock-concrete interface);
- Seepage (weir at the downstream toe of the dam).

The material properties that were considered in the design studies of the dam are provided by the formulators. In this document, explanation on the monitoring system, data collection and pre-processing is provided as well. The geometry of the dam is provided in different CAD formats.

1.4 Schedule

The timeline of the 2022 Benchmark Workshop workflow is the following:

- **July 2021:** Detailed description of the topic will be provided by the formulators.
- **October 2021:** Deadline to announce interest in the topic. The formulators will establish contact with the participants that have announced their interest.
- **January 2022:** Paper template published on the workshop webpage.
- **February 2022:** Deadline for the participants to submit their results to the formulators.
- **February 2022:** Deadline to submit full paper for the workshop.

- **March 2022:** Presentation template published on the webpage, participants will be provided with instructions on which content to include in their presentations and what to omit.

- **5.-7. April 2022:** Benchmark Workshop in Ljubljana, Slovenia.

2 Description of the case study

2.1 Introduction

The dam is located in the south of France. It is owned by EDF and is referred to as 'Dam_EDF' in the following text. Dam_EDF was constructed between 1957 and 1960. It is a double curvature arch dam, which is asymmetric due of the shape of the valley. Dam_EDF consists of 13 blocks as follows:

- 1 block on the right bank with a width of 12 m
- 11 blocks, each with a width of 12.5 m
- 1 block on the left bank with a width of 17 m

In Figure 1 and Figure 2, illustrations of the dam are presented. The foundation of Dam_EDF consists of laminated metamorphic slate with a high compressive strength. However, the anisotropy of foundation confers a higher deformability to the left bank.

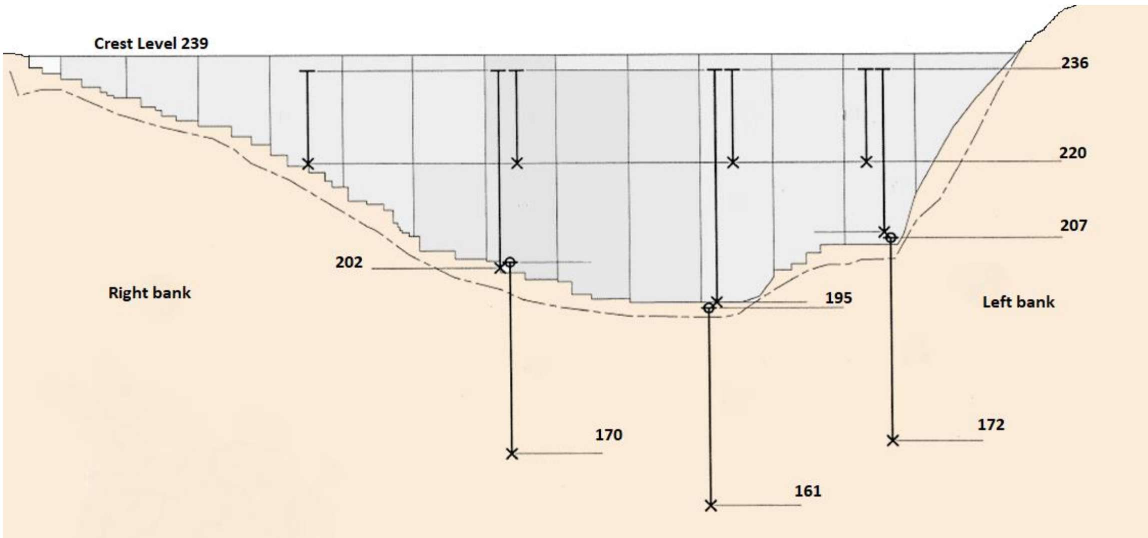


Figure 1 - Downstream view of Dam_EDF used as case study for Theme A.

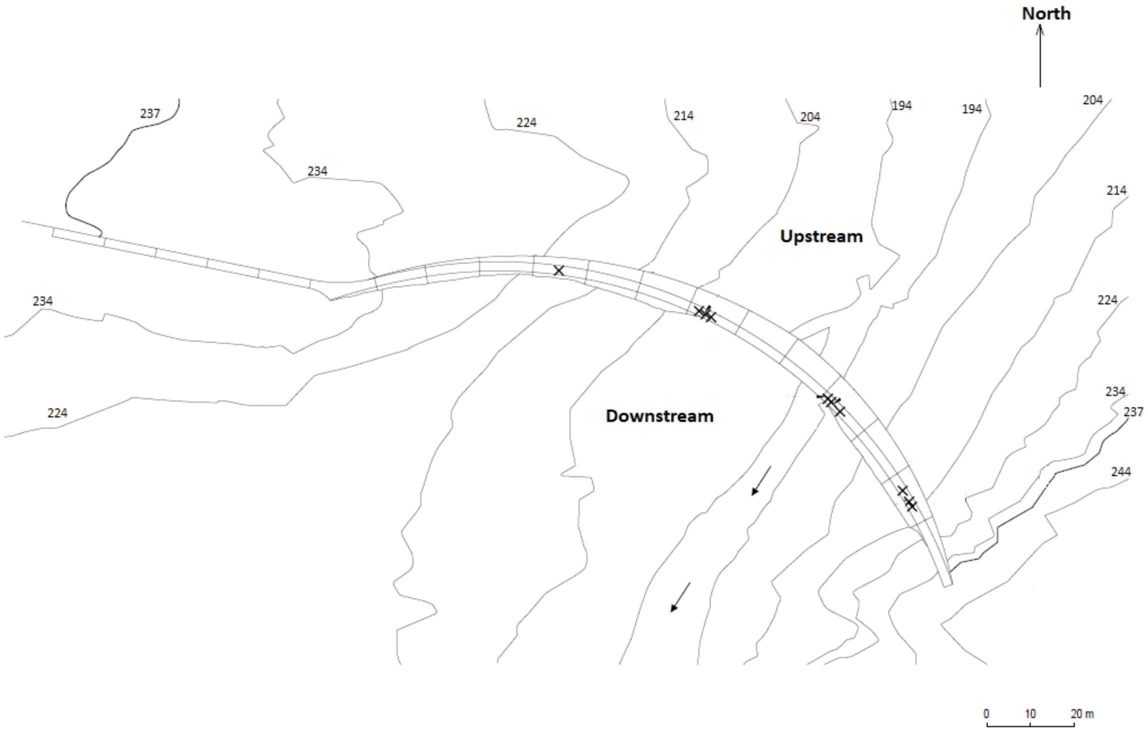


Figure 2 – View from the top. The crosses indicate the position of the pendulums.

2.2 The dam

2.2.1 Geometry

The main technical data are:

- Dam height above foundation 45 m
- Crest thickness 2 m
- Base thickness 6 m
- Crest radius 110 m (90°)
- Crest length 166 m
- Ratio crest length/dam height 3.7
- Normal Water Level * 237 m
- Crest Level * 239 m

* In the following text, all altitudes refer to a common value which is an arbitrary value, and <u>not</u> the sea level. The water level in the reservoir, altitudes of pendulums and piezometric levels refer to this arbitrary value. The unit of the altitude is meter [m]. It should be noted that the real altitude of the Dam_EDF is approximately 2000 m above sea level.

2.2.2 Material properties

Dam_EDF is made of concrete with cement dosage at 300 kg/m^3. The average value of compressive strength is 34 MPa (after 90 days) with values varying from 22 MPa to 45 MPa. More details regarding material properties that can be used for finite element simulations are presented in the Appendix.

2.3 Measurements

2.3.1 Introduction

Dam_EDF is equipped with a comprehensive monitoring system, including pendulums, crack opening displacement sensors, piezometers and seepage measurements. Monitoring data have regularly been acquired since the first impoundment. The measurements are automatically checked with a delay of 48 hours after acquisition. In the event of a suspicious or erroneous measurement, the measurement process is restarted, and if the error is due to the measuring device, it is replaced or upgraded. Only valid measurements are stored in the database. Thus, the provided data in this benchmark is the reference and valid data for behaviour analysis and does not need any further cleaning.

2.3.2 Water level

Time series of water level are provided from 1995 to 2017. The time format is common to all time series given in this benchmark: day/month/year hour:minutes:seconds (dd/mm/yyyy hh:mm:ss). For water level in the reservoir, there is at least one value per day. The unit of water level is meter [m]. The reference of altitudes is indicated in the subsection 2.2.1.

It should be noted that when the water level is lower than +196 m, the whole upstream surface is exposed to ambient air temperature. This can happen because Dam_EDF is located on the top of a glacial threshold. Hence, when water level is lower than +196 m, there is only water in a lake located upstream and below the heel of Dam_EDF.

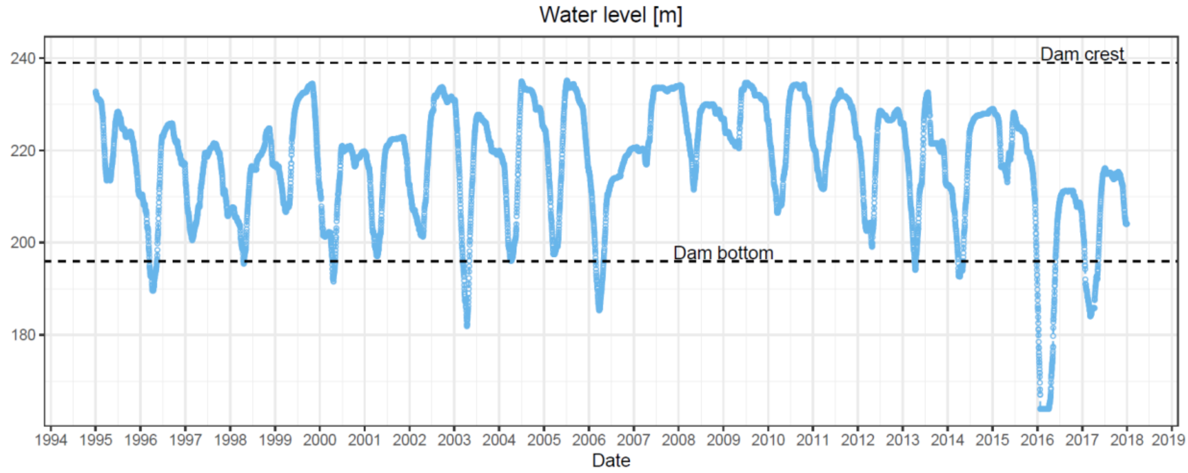


Figure 3 – Time series of water level in the reservoir.

2.3.3 Air temperature

The air temperature is not measured at the location of the dam. However, two time series of daily air temperature are given:

- T_a, which is a time series of measurements located in the area of the dam. The measurements are carried out according to the standard of WMO (World Meteorological Organisation) and are located 50 km from the dam, however at a different altitude.
- T_b is calculated by interpolation from several air temperature measuring stations. The interpolation takes into account the altitude of the dam and is calculated on a mesh of 1 square kilometer.

Time series of air temperature are provided from 1995 to 2017 and the unit is °C (degree Celsius).

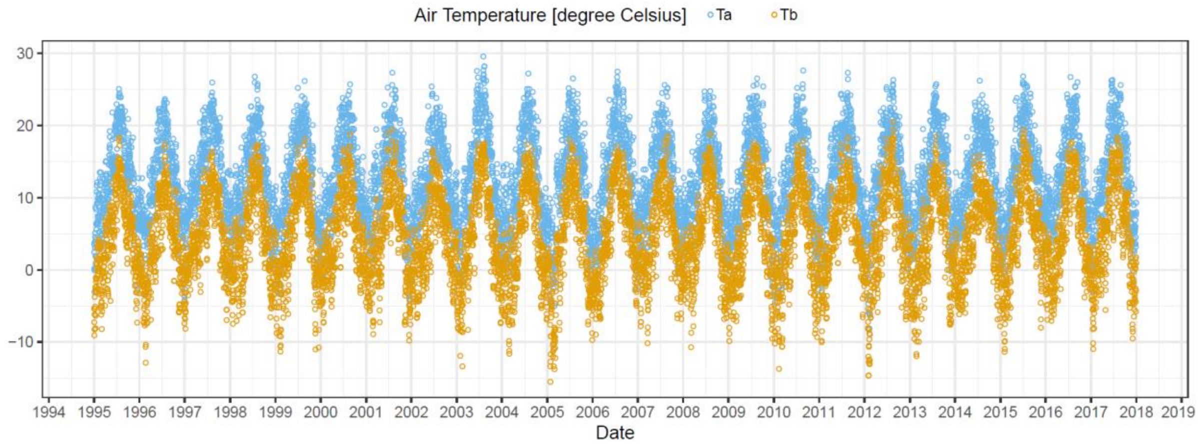


Figure 4 – Time series of air temperatures T_a and T_b.

2.3.4 Rainfall

Data from a rain gauge located about 5 km from Dam_EDF is provided. The daily cumulative precipitation time series is provided from 1995 to 2017. The unit of precipitation is mm.

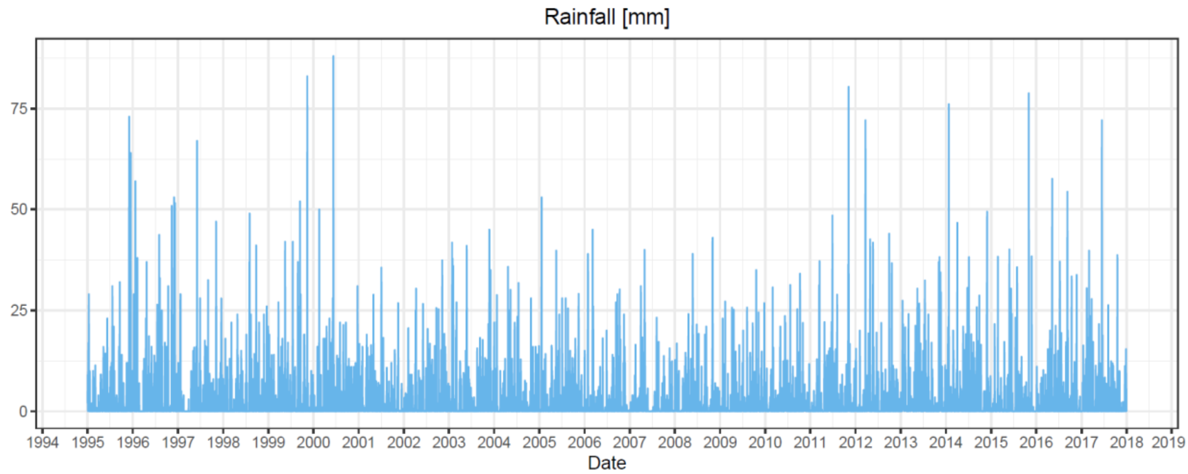


Figure 4 – Time series of daily rainfall (mm).

2.3.5 Pendulums

The dam is equipped with several pendulums, as illustrated in Figure 5 below.

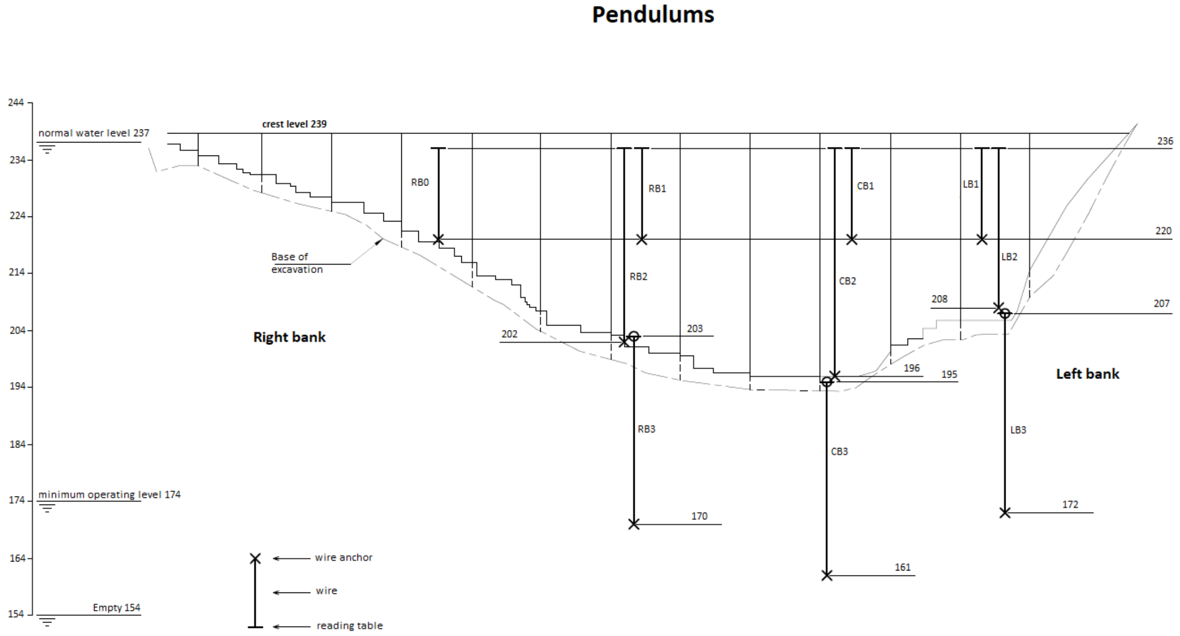


Figure 5 – Location of pendulums (downstream view).

For this benchmark, only the measurements of pendulums on the Central Block (CB) are given, see Figure 6. The time series of CB2 and CB3 are given from 2000 to 2012. CB2 is the radial displacement between the altitudes 236 m (just under the crest of Dam_EDF) and 196 m (toe of Dam_EDF). CB3 is the radial displacement in the foundation between the altitudes 195 m and 161 m.

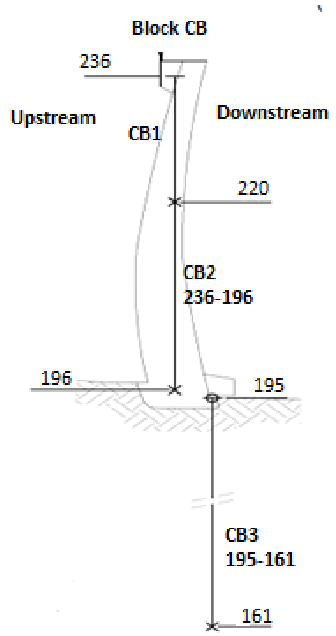


Figure 6 – View of block CB and pendulums

The provided radial displacements measured using the pendulums is presented in Figure 7. An increasing radial displacement indicates a movement of the highest point in the downstream direction. The unit of displacements is mm.

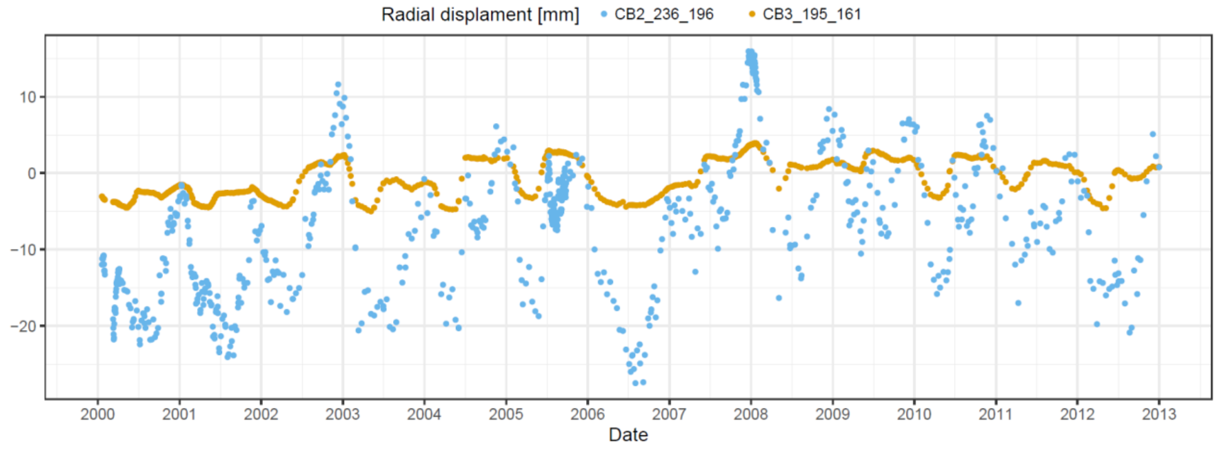


Figure 7 – Time series of pendulums CB2 and CB3.

2.3.6 Crack opening displacements sensor

A crack opening displacement sensor is located at the rock-concrete interface of the Central Block (CB). The sensor measures the opening between C4 (in the foundation) and C5 (in the concrete, at the toe of the dam). The location of the sensor is illustrated in Figure 8.

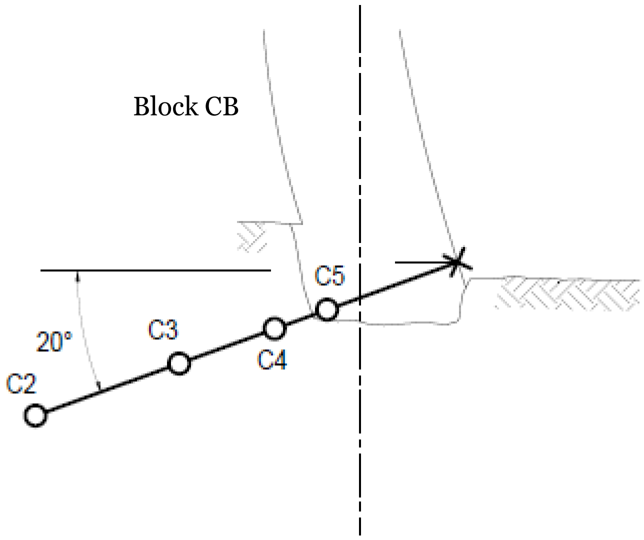


Figure 8 - Location of crack opening displacements sensor in the block CB.

The time series of the relative distance between C4-C5 is given in the Excel file. The data is given from 2000 to 2012 as seen in Figure 9. An increasing value of C4-C5 means that the distance between C4 and C5 is increasing. The unit of displacement is mm.

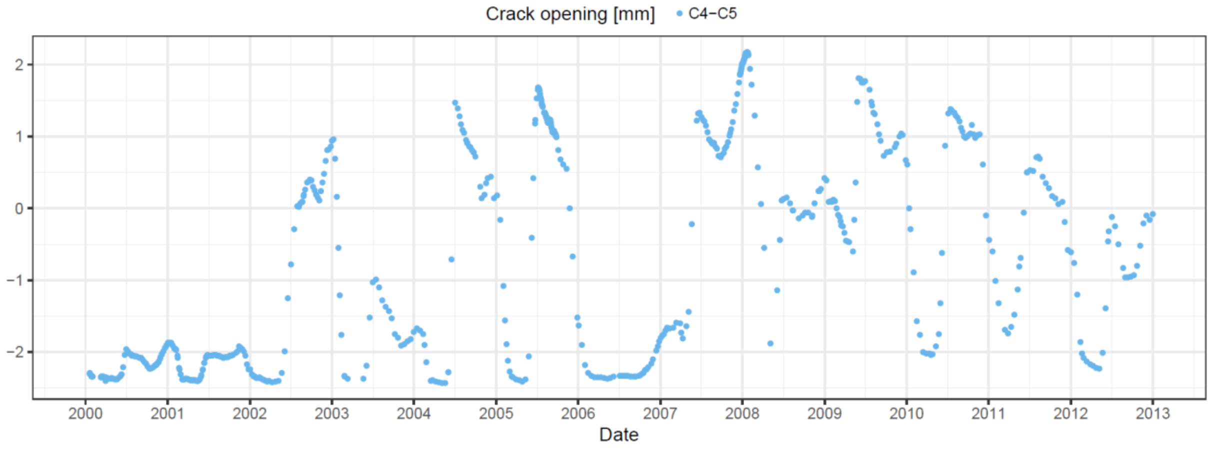


Figure 9 – Time series of crack opening displacements.

2.3.7 Piezometers

For this benchmark, the focus is on the piezometers located in the block CB. Their location in the block CB are indicated in Figure 10 below.

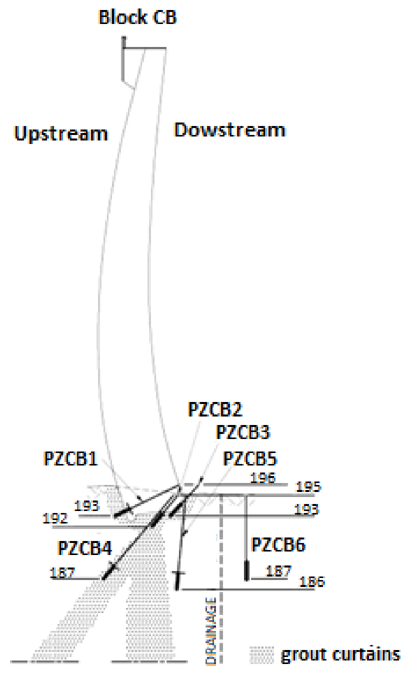


Figure 10 – Location of piezometers in the central block CB.

PZCB4, PZCB5 and PZCB6 are embedded deeply in the foundation and will not be analysed in this benchmark. PZBC1 is located at the upstream of the grout curtain and thus its levels are quite equal to the hydraulic head. Consequently, PZCB1 is not analysed in this benchmark.

Time series of piezometric levels PZCB2 and PZCB3 are given from 2000 to 2012. The unit of piezometric levels is meter (m). The reference for altitude is the same as for water level and elevations (Figure 4) and is indicated in the subsection 2.2.1.

The time series of PZBC3 contains missing values from the 5th of February 2008 to the 10th of September 2008. A leakage in the standpipe of piezometer PZBC3 was observed during this period that is why measurements were removed. In September 2008, a cleaning of the drainage system was carried out.

This work needs to be taken into account when analysing monitoring data. One could for instance split the calibration period into two parts.

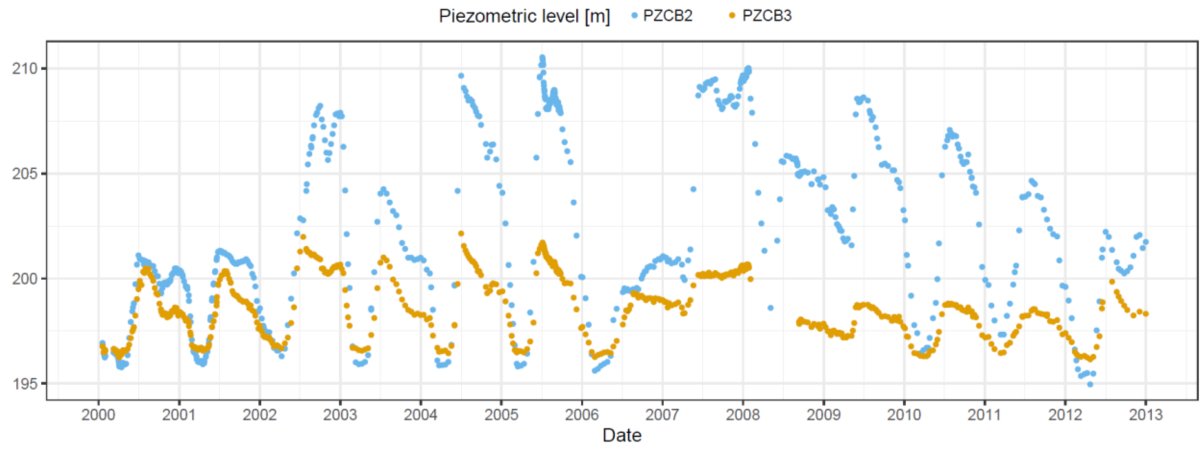


Figure 11 – Time series of piezometric levels PZCB2 and PZCB3.

2.3.8 Seepage

The total seepage flowrate of Dam_EDF is also provided. The flowrate is measured using a weir located in the gallery at the downstream toe of Dam_EDF. The measured total seepage is the total amount of water originated from different locations such as the surrounding rock, moisture transport in concrete, potential leakages in concrete cracks and the drainage system. Times series of flowrate are given from 2000 to 2012 and the unit is L.min-1 (Litre per minute)

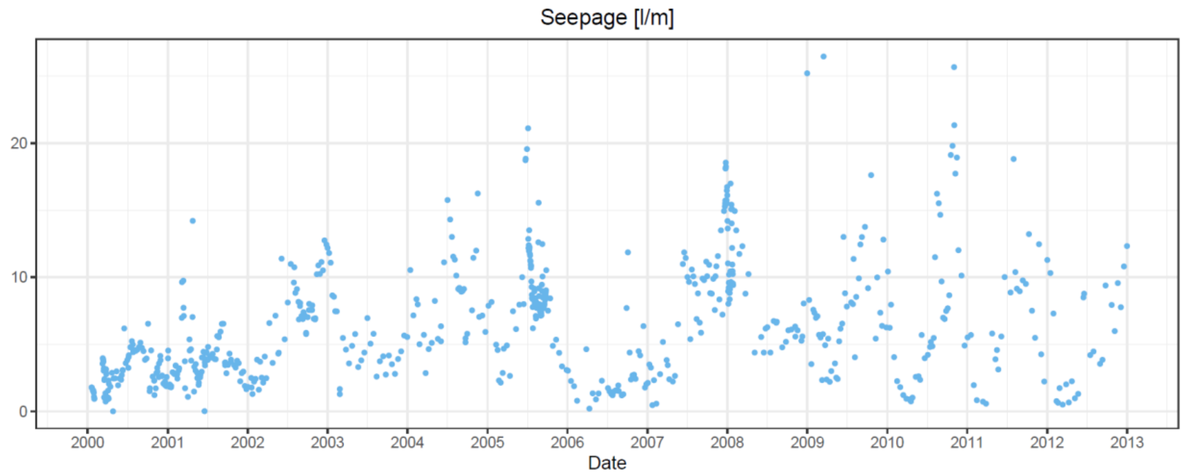


Figure 12 – Time series of seepage.

3 Delivered data from formulators

3.1 Data preparation

As mentioned in Section 2.3, variables are measured with different and irregular frequency. One of the goals of this Theme is to compare criteria to handle the data preparation caused by issues that may appear in practise such as resampling, missing values, etc. Therefore, the dataset is provided without any modification of the actual time series. The main features of the provided data are summarized in Table 1.

Table 1 – Summary of the main features of the provided data.

Variable type [units]	Variable name	Period	Average reading frequency	# Measurements
Water Level [m]	Water Level	1995-2017	1 day	9736
Air Temperature [°C]	T_a	1995-2017	1 day	8401
	T_b	1995-2017	1 day	8401
Rainfall [mm]	Rainfall	1995-2017	1 day	8401
Radial displacement [mm]	CB2_236_196	2000-2012	1.5 weeks	703
	CB3_195_161	2000-2012	1.5 weeks	698
Crack Opening [mm]	C4-C5	2000-2012	1.5 weeks	676
Piezometric level [m]	PZCB2	2000-2012	1.5 weeks	705
	PZCB3	2000-2012	1.5 weeks	670
Seepage [l/min]	Seepage	2000-2012	1.5 weeks	672

The most appropriate format of the time series depends on the chosen model (either FEM or data-based) and the software tool used. The participants will receive the data in three different versions to facilitate the analysis:

1. An excel file with each variable in a different sheet ('ThemeA_data_fmt01.xlsx'). It should be noted that the time vector differs among variables, due to the different reading frequency and reading period.
2. An excel file with all variables in one sheet ('ThemeA_data_fmt02.xlsx'). The time vector encompasses all time stamps from all variables. Since this includes the hour, several rows appear for the same day in case more than one record was taken at different hours.
3. An excel file with all variables in one sheet with a common time vector in the format dd/mm/yyyy ('ThemeA_data_fmt03.xlsx'). This is a transformation of the original dataset: if more than one record is available for some variable within one day, the mean value is taken. As a result, the number of records is lower than in the original dataset.

In all versions, the cells in the forecasting period for the output variables are left blank. Participants can explore the provided data by loading either the second or the third versions into the free online app: https://cimnetest.shinyapps.io/PREDATOR/[1].

The participants are free to use any version of the data for each part of the analysis.

3.2 Data-based models

Participants are free to use their preferred software or algorithm to compute predictions and warning levels.

In general, the dam response is assumed to depend on the acting loads —mainly hydrostatic load and temperature— and time. Therefore, the general expression of a predictive model can be written as:

$$M(t, env) = P(t, env) + D(t, env)$$

[1] Contact cimnemadrid@cimne.upc.edu for more information or help.

where,

$M(t, env)$ is the measured value, depending on time (t) and environmental conditions (env); $P(t, env)$ stands for the predictions, and $D(t, env)$ corresponds to the difference between observations and predictions.

The general expression for a predictive model based on monitoring data can be written as:

$$P = a_1 + f_1(h) + f_2(T) + f_3(t) + \varepsilon$$

where P stands for the predicted value, a_1 is a constant; the functions $f_1(h)$, $f_2(T)$, and $f_3(t)$ represent respectively hydrostatic, thermal, and irreversible effects; ε is the prediction error, encompassing all effects not considered by the model.

The particular expression for each function depends on the method used. The most popular data-based approach for dam monitoring analysis is the hydrostatic-seasonal-time (HST) model. It was first proposed by Willm and Beaujoint in 1967 [1] to predict displacements in concrete dams, and has been widely applied ever since. With this approach, the form of the abovementioned functions is:

$$f_1(h) = a_0 + a_1 h + a_2 h^2 + a_3 h^3 + a_4 h^4$$

$$f_2(h) = a_5 \cos(s) + a_6 \sin(s) + a_7 sin^2(s) + a_8 \sin(s)\cos(s)$$

Where

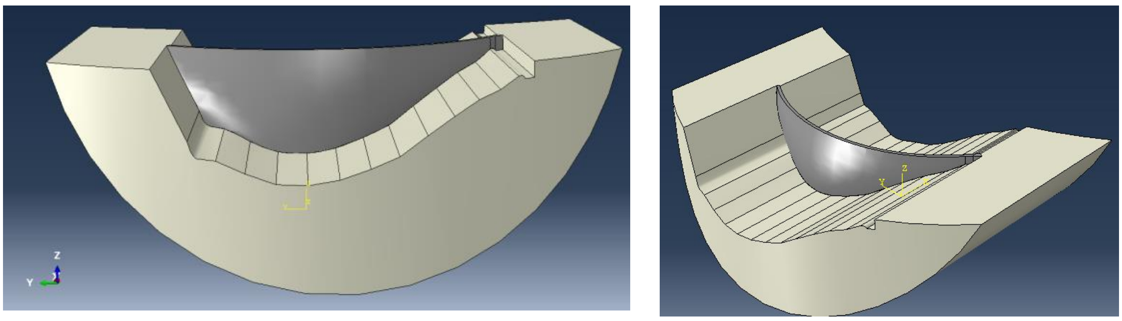
$$s = \frac{2\pi d}{365.25}; d = calendar\ day$$

$$f_3(t) = a_9 \log(t) + a_{10} e^t$$

Other statistical methods have also been used for this purpose. Examples include neural networks [2], [3], support vector machines [4] and boosted regression trees [5], among others [4], [6].

3.3 Numerical FE model

A geometrical model has been developed by the formulators and is provided to the participants of the benchmark workshop. The geometry consists of two separate parts; the concrete arch dam (including the abutment) and the rock foundation. In this geometry, the dam is described as a monolithic structure.



a) b)

Figure 13 – Illustration of the geometry of the arch dam and foundation used as a case-study for the theme.

3.3.1 Geometry files

The geometry of the dam is provided in different CAD-based file formats that can be imported into most of the existing finite element codes

- ACIS .sat
- STEP .stp
- IGES .igs

3.3.2 Mesh file

Defining a suitable mesh is an important part of numerical analyses, and the requirement of the mesh, regarding the size of the elements, depends on many factors, such as defined material behaviour, type of loads considered etc. Therefore, even though one suggestion for mesh is provided by the formulators, it may be required that the participants define a mesh of their own that is suitable for their analyses.

An input-file in ASCII code (.inp) is provided with the raw data of the coordinates of all nodes and the topology of the elements in the FE-model.

The dam has been meshed with 4-node linear tetrahedron elements (C3D4 in Abaqus), with a typical length of about 1.0 m. The concrete parts consist of 32 195 nodes and 155 780 elements.

The rock foundation has been meshed with 4 node linear tetrahedron elements (c3D4 in Abaqus), with a typical length of about 1.0 m at the rock-concrete interface and 20 m near its exterior surfaces. The rock parts consist of 7 224 nodes and 31 073 elements.

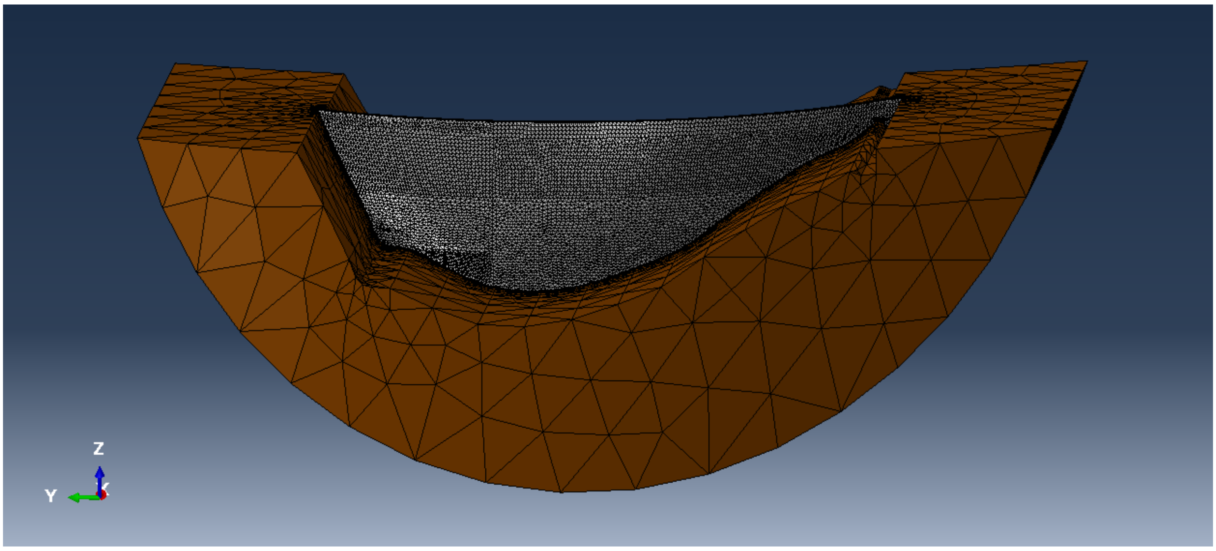


Figure 14 – Illustration of the geometry of the arch dam and foundation used as a case-study for the theme.

The convention used for element definition in Abaqus is illustrated in the figure below. This figure shows the node numbering for the element type that is provided in the input-files.

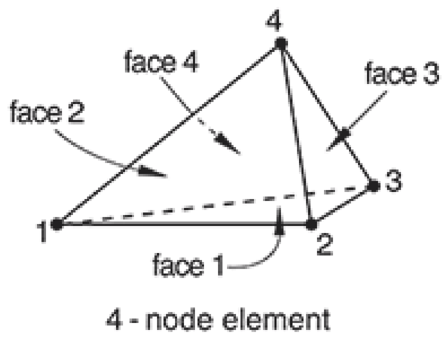


Figure 15 – Illustration of the numbering convention for the elements used in the provided mesh.

3.3.3 Requirements on the FE analyses

The participants are free to perform the finite element analyses in any way that they find suitable. Thereby, to allow for large freedom in the modelling choices for the participants, no further information will be presented in this section. However, if the participants want some guidance on suitable initial assumptions for their first model definition, a more detailed description is presented in the Appendix.

4 Case studies and tasks

The Theme is organised in three Cases, in accordance with the period of analysis.

- Calibration (Case A): 2000-2012.
- Short term prediction (Case B): January 2013 - June 2013
- Long term prediction (Case C): July 2013 - December 2017

For all cases and each output variable, the participants are requested to submit:

1. A vector of the predictions, with one value for each time stamp in the provided time series
2. Two vectors of lower and upper warning thresholds

The time series for both the input variables and the dam responses are provided for the period 2000-2012. They can be used to calibrate the parameters of the models: material properties, boundary conditions and other features of FEM, and training parameters for data-based models.

Records of rainfall, water level and air temperature are provided from 1995. Participants using FEM models may find this information useful for computing the thermal and stress field of the dam at the beginning of the calibration period.

Predicted values should be the best estimate of the dam response in terms of each of the output variables. These predictions will be compared to the actual measurements by the formulators.

Participants are free to define the warning thresholds with their own criterion. Narrow thresholds may result in false anomalies, while wide ranges are less useful for detecting unexpected behaviour, malfunctioning sensors, etc. The formulators will verify if some actual measurement is out of the proposed warning threshold.

In addition to the predictive task, it is requested to perform one interpretive task. The interpretation task should be considered as a general analysis of the dam, measurements, data and modelling in the context of dam safety. The participants should explain how their analysis and results could teach us anything about the dam's performance, if the model can provide support for the decision-making process, etc. This task should be considered as very open: you may decide to perform risk analysis, assess maintenance needs, failure simulations, establish link between external load and monitored phenomenon, or any other approach based on your judgement, experience, and motivation.

For example, for the conventional HST model, the contribution of each external load and that of time can be associated to the value of the coefficient in the calibrated model. An example plot for showing the contribution of each load is included in Figure 16.

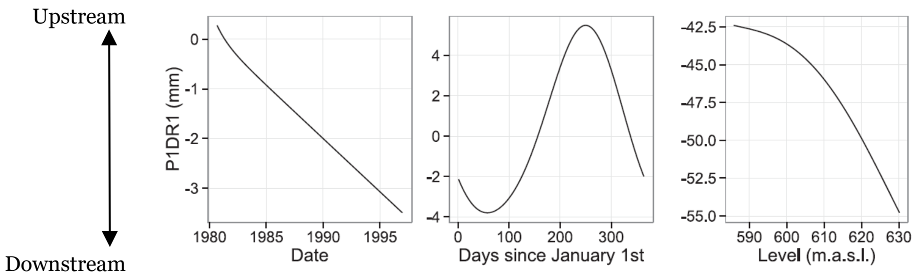


Figure 16 – Example plot for the contribution of the environmental variables from an HST model for a radial displacement [7].

Machine learning methods may require specific processes for this interpretation. For instance, sensitivity analysis can be applied, in which each external variable is modified at a time, while keeping the others at a reference value. These results can be plotted to show the linear/nonlinear influence, threshold effects, etc. Also, the range of variation of the predicted response can be an indicator of the importance of each input. Participants are encouraged to show the contribution of the external variables in a similar format as mentioned for HST. In the example in Figure 17, partial dependence plots [8] are shown from a model based on Boosted Regression Trees, for time, temperature and water level.

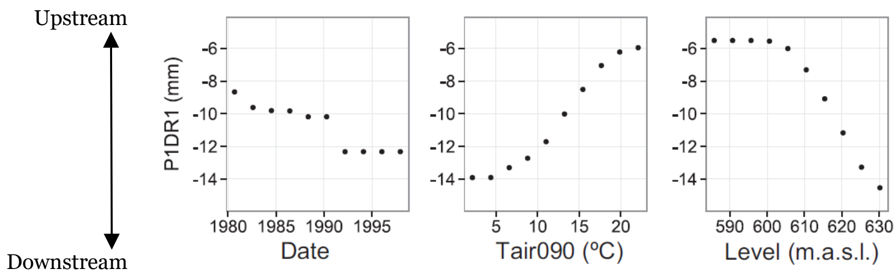


Figure 17 – Example of interpretation of ML models. Effect of time, temperature and hydrostatic load on the radial displacement of an arch dam, computed from the partial dependence plots in a model based on Boosted Regression Trees [7].

The proposed tasks are summarised in Table 2.

Table 2 – Summary of the mandatory and optional tasks.

Target variable	Interpretation	Case A: calibration		Case B: Short term		Case C: Long term	
		Prediction	Warning levels	Prediction	Warning levels	Prediction	Warning levels
CB2_236_196	Mandatory	Mandatory	Optional	Mandatory	Mandatory	Mandatory	Mandatory
CB3_195_161	Mandatory	Mandatory	Optional	Mandatory	Mandatory	Mandatory	Mandatory
C4-C5	Optional	Optional	Optional	Optional	Optional	Optional	Optional
PZCB2	Optional	Optional	Optional	Optional	Optional	Optional	Optional
PZCB3	Optional	Optional	Optional	Optional	Optional	Optional	Optional
Seepage	Optional	Optional	Optional	Optional	Optional	Optional	Optional

4.1 Required output

The participants should deliver their results to the formulators of the theme via the provided excel template files. In these template files, the first section is used for participants to provide general information about their group, which will help with the synthesis of the results (experience, software used, consumption of time, etc.).

For Cases A, B, and C, the spreadsheets contain time stamps for each variable, where the participants are asked to copy the prediction vectors, with one value for each time stamp, and two vectors for the lower and upper thresholds, respectively. It is very important to provide the result only for the required time stamps. Therefore, some of the cells in the document are locked. Radial displacement results are mandatory, while other variables are optional. For the participants using FE models, Figure 18 presents the points of interest from which displacements and joint openings should be obtained.

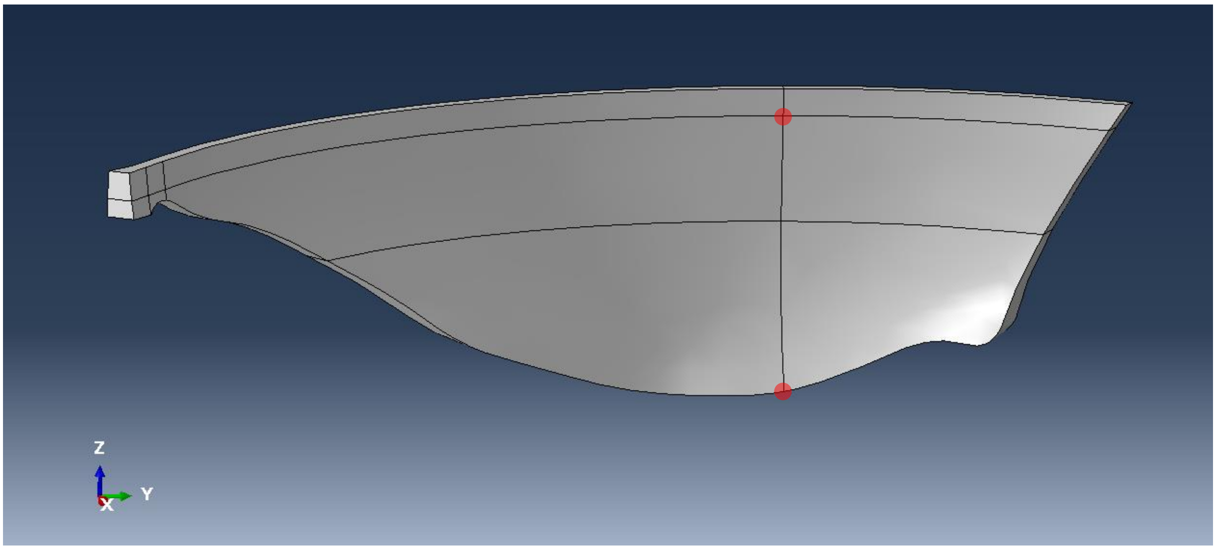


Figure 18 –Locations of the points of interest in the FE model.

Before the submission of the Excel files, please name them in the following manner: **Surname*-Theme-A.xslx**. If multiple methods are used, each method should be submitted in a separate file, and the participants should mark them with consecutive numbers. The method denoted as no. 1 is then interpreted by the formulators as being the best guess from the participant.

The excel templates are intended to provide the formulators with technical information, which will be used for the analysis and comparison of the results. In addition, every team is also asked to prepare a paper to be included in the workshop proceedings. Template of the paper will be provided by the organizers and will be uploaded to the workshop's webpage. The paper should:

- Explain modelling assumptions and approaches used when preparing the model; for example, the version of the monitoring data taken as starting point, the transformations applied, theoretical explanation of the model and software implementation.

- Explain the calibration process, which variables were used to calibrate numerical model, and which were used as training parameters for data-based models. Explain any pre-processing of the variable frequency in the measured data-set. Specifically, for data-based models, describe if cross-validation or similar process was followed.

- Provide a general interpretation of the model e.g. how can the model be used to support the decision making process for dam safety, what can we learn from the model, was any strong correlation between certain variables found, what can be predicted from that correlation, which is the most suitable variable (or combination of variables), according to the analysis and interpretation, to use when defining alarm and alert levels...

- Provide additional results, for example, participants using FE models are encouraged to include representative contour plots.

- Provide discussion on long-term and short-term predictions, lessons learned, and general observations on the parameters that influence the result.

The full paper should contain a unique title of the paper, information about the authors, their affiliations, the e-mail address of the corresponding author, a short abstract, the main body of the paper, a conclusion, optional acknowledgements and references. The length of the full paper is from 10-12 pages, without references. Paper template will be published on the Workshop's webpage in January 2022.

Workshop presentations should highlight specific information's regarding the lessons learned by the participants and specific steps to solve the tasks. The formulators will provide an introductory presentation of the Theme A, Case studies, the dam and provided data, so the participants can focus only on the specific details of their work. A template for the presentation and more detailed instructions on the preparation of the presentation will be provided roughly one month prior to the Workshop in Ljubljana.

4.2 Timeline

A rough estimation of the time to solve the tasks of the Theme A is presented below. The time estimated to solve the theme is between 6 to 13 working days for the mandatory tasks. Additionally, participants will need time to prepare the conference paper and presentation.

Table 3 – Estimation of time required to participate in the theme

Analysis	Time estimation (working days)
Preparation of the data	2-3
Case A: Calibration	2-5
Case B: Short-term	0.5-1
Case C: Long-term	0.5-1
Interpretation	1-3
Total time needed	6-13

Time estimation in Table 3 refers to the usage of data-based models. Participants who will use FEM models may require more time, likely in the higher range of these estimations. The time specified above also varies due to the ambition and experience of the participants. In addition to the time specified above, the participants also need time to write the conference paper. The time needed for this is considered to be very individual and hence not estimated here.

4.3 Scoring

The participants are free to use and report whichever cost function deemed suitable for their calibration. However, during the workshop and in the proceedings the predictions for the short and long-term will be evaluated by comparing the predictions (P_i) with the real measured data (Y_i) in terms of the following metrics:

Mean Absolute Error (MAE):

$$MAE = \frac{1}{N}\sum_{i=1}^{N}|Y_i - P_i|$$

where N is the number of time stamps in the corresponding period (either short or long-term)

Normalized Root Mean Squared Error (NRMSE):

$$NRMSE = \frac{\sqrt{\frac{\sum_{i=1}^{N}(Y_i - P_i)^2}{N}}}{Y_{max} - Y_{min}}$$

Special attention will be paid to both short and long-term predictions, since in case of overfitting, data-based models can be highly accurate for the training set and offer poor predictions when predicting new data.

The warning thresholds will be assessed by means of the quantity of records considered as potentially anomalous for each period, i.e., values above the upper bound or below the lower bound.

The predictions from the participants will be anonymized in all comparisons to ensure that the focus remains on the models. However, the combination of a limited number of participants and models may enable identifying unique contributions in the aggregated analysis.

5 References

[1] Willm G, Beaujoint N (1967) Les méthodes de surveillance des barrages au service de la production hydraulique d'Electricité de France-Problèmes ancients et solutions nouvelles. In: 9th ICOLD Congres, pp 529–550, q34-R30. [in French]

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A Appendix

In this appendix, some more detailed information is given intended for the participants that perform finite element analyses of the concrete arch dam. It should be noted that the information given in this appendix is not mandatory, instead it should be seen as recommendations for those who seek some guidance regarding their models. Additional tips can also be found in [9].

The suggestions given in this section can be seen as an initial assumption that can be used to develop preliminary models. The participants are encouraged to perform model updating to ensure good correlation between calculated and measured behaviour, hence many of the suggested properties given in this section may be updated during model calibration.

The information given in the appendix are only describing the type of analyses (thermo-mechanical analyses) that are required to be performed in order to solve the mandatory part of this Theme. In case any participant wants to use finite element models (or equivalent) for solving the optional tasks, then also pore pressure analyses (seepage analyses) are required (thermo-hygro-mechanical).

A.1 Material properties

In this section, suggestions for initial assumption of material properties are presented. The participants should update these if needed based on the outcome of the model calibration.

As mentioned in the main part of the formulation document, see Section 2.2.2, the concrete was made with a cement dosage at 300 kg/m^3. The average value of compressive strength is 34 MPa (after 90 days) with values varying from 22 MPa to 45 MPa.

A.1.1 Thermal material properties

In the thermal analyses, representative material properties should be defined for the concrete and rock foundation. Below, suggestions for material properties for the initial assumption of the material properties are given.

Table A.1 – Initial thermal material properties for concrete.

Property	**Value**	**Unit**
Poisson’s ratio	0.2	-
Density	2400	kg/m^3
Thermal conductivity	2	W/(m*K)
Specific heat capacity	900	J/(kg*K)

Table A.2 – Initial material properties for the rock foundation.

Property	**Value**	**Unit**
Poisson’s ratio	0.2	
Density	2700	kg/m^3
Thermal conductivity	3	W/(m*K)

Property	Value	Unit
Specific heat capacity	850	J/(kg*K)

The reference temperature, strain free temperature, is important for thermo-mechanical analyses. It may vary in different parts of the dam. In this case, the reference temperature for both concrete and rock can be assumed equal to the mean annual temperature unless a better assumption can be made.

A.1.2 Mechanical properties

During the design studies of the dam, the following characteristic material properties of the concrete were used:

- Young's modulus for concrete: 10^4 MPa (voluntarily underestimated to model the effect of creep)
- Coefficient of expansion of concrete: $7 \cdot 10^{-6}$ K^{-1}

In the later, more detailed, finite element analyses of the dam made, the material properties presented in Table A.3 were used for the dam.

Table A.3 – Material properties used in previous assessment of the dam.

	Young's Modulus [GPa] $E_{//}$	Young's Modulus [GPa] $E_{\perp}$
Concrete of the dam	22	-
Foundation right bank	15	10
Foundation (approximately bottom of the valley)	5	1
Foundation left bank	10	1

Other material properties that are required for the mechanical analyses are the Poisson's ratio and the density. It is suggested that the following properties are used;

- Density 2400 kg/m^3
- Poisons ratio 0.2

If participants find a need for considering non-linear material behaviour, such as concrete cracking, suitable material properties should be defined.

A.2 Types of analyses

Two different types of analyses are required in order to perform the mandatory part of this theme. The mandatory part of this theme requires that participants perform thermal analyses that results in temperature distributions in the dam. Additionally, in order to obtain output that can be used to calibrate and predict the required output, also a mechanical finite element analysis is required.

The participants can perform these analyses in any way that they find suitable, but it is normally considered sufficient to include a one-way coupling between the thermal analysis and the mechanical analysis.

In order to solve some of the optional tasks, a third type of finite element analysis is required that can describe the seepage. For this type of an analysis, typically a pore-pressure simulation is performed. It is also recommended that this analysis is performed as transient (thereby considering the time).

A.2.1 Thermal analyses

Conclusions from previous benchmark workshops have shown that transient thermal analyses along with Robin type of boundary conditions are recommended to capture the temperature distributions accurately, see [10].

The participants can use an alternative approach to model the temperature variation, however in this section, suggestions for properties for performing such an analysis is given.

To ensure that an accurate temperature distribution is present in the dam when the mechanical analysis is performed, it is recommended to start the thermal analyses a certain period earlier, for instance starting already from 1995.

A.2.1.1 Loads / Interactions

The ambient air temperatures were already presented previously in Section 2.3.3. It is up to the participants to choose which of the provided temperature variations should be considered and how. For instance, the participants have to choose if the temperature is considered to be constant over the surfaces or varying in different regions. They also have to determine a suitable time step that can be considered to capture the important aspects that governs the dam behaviour. Information related to the influence of solar radiation has for instance not been provided, but if some participant wants to consider this, then the orientation of the dam illustrated in Figure 2 can be of some help.

The temperature in the water is unfortunately not measured and hence has to be assumed by all participants using finite element modelling. The following expression is suggested as an initial assumption:

$$T_{water} = \begin{cases} 0.7 \cdot T_{air} & if\ T_{air} > 0\ ^{\circ}C \\ 0 & otherwise \end{cases}$$

It is suggested that the water temperature is considered to be constant over the depth as a first assumption. As seen in the water elevation measurements, the reservoir level is sometimes quite low, which results in that significant parts of the upstream surface or the entire upstream surface is subjected to ambient air temperatures during these times.

Suggestions for the convective heat transfer coefficients are presented in Table A.4.

Table A.4 – Suggested convective heat coefficients

Parameter	Convective heat coefficient (W / (m^2 K))
Concrete – air	13
Concrete – water	500
Concrete - rock	1000
Rock – air	13
Rock - water	500

A.2.1.2 Boundary conditions

Adiabatic thermal conditions or other relevant thermal conditions should be placed on the bottom of the rock foundation.

A.2.2 Mechanical analyses

The mechanical analyses should preferably be performed in different steps. This is especially important if non-linear contact at the concrete-rock interface is considered. Typically, it is recommended to apply the gravity loads first and after this apply the varying hydrostatic water pressure and the varying temperature distributions.

A.2.2.1 Loads

The participants should consider all the relevant loads for simulating the normal and expected behaviour of the dam.

Example of such loads can be

- Gravity load
- Hydrostatic pressure
- Uplift pressure

A.2.2.2 Interactions

As one of the important variables used for assessing the dam behaviour is the joint opening, it is important that the participants define that the joint is allowed to open if tensile forces occur.

A.2.2.3 Boundary conditions

The participants should define relevant boundary conditions for the analyses.