Book Part, Published Version

Fleischer, Helmut; Schlegel, Roger; Goldgruber, Markus

Investigation of the probability of failure of a gravity dam

Verfügbar unter/Available at: https://hdl.handle.net/20.500.11970/106962

Vorgeschlagene Zitierweise/Suggested citation:
Fleischer, Helmut; Schlegel, Roger; Goldgruber, Markus (2018): Investigation of the probability of failure of a gravity dam. In: Proceedings of the Symposium Hydro Engineering; ICOLD 2018, 26th Congress – 86th Annual Meeting Graz: Verlag der Technischen Universität Graz. S. 1460-1471. https://www.icoldaustria2018.com/fileadmin/ICOLD_Austria_2018_Book_of_Full_Papers_Symposium.pdf.

COMMISSION INTERNATIONALE DES GRANDS BARRAGES

VINGT-SIXIÈME CONGRÈS DES GRANDS BARRAGES
Autriche, juillet 2018

DOI 10.3217/978-3-85125-620-8-132

INVESTIGATION OF THE PROBABILITY OF FAILURE OF A GRAVITY DAM

Roger SCHLEGEL

DYNARDO GMBH

GERMANY

Markus GOLDGRUBER

DYNARDO AUSTRIA GMBH

AUSTRIA

Helmut FLEISCHER

FEDERAL WATERWAYS ENGINEERING AND RESEARCH INSTITUTE (BAW)

GERMANY

COMMISSION INTERNATIONALE
DES GRANDS BARRAGES

VINGT-SIXIÈME CONGRÈS DES
GRANDS BARRAGES
Autriche, juillet 2018

INVESTIGATION OF THE PROBABILITY OF FAILURE OF A GRAVITY DAM

Roger SCHLEGEL

DYNARDO GMBH

GERMANY

Markus GOLDGRUBER

DYNARDO AUSTRIA GMBH

AUSTRIA

Helmut FLEISCHER

FEDERAL WATERWAYS ENGINEERING AND RESEARCH INSTITUTE (BAW)

GERMANY

1. INTRODUCTION

Within the framework of an in-depth review of an old gravity dam in Germany [1], detailed safety assessments are carried out according to the latest state of standardization. Tremendous work has already been done on this topic and especially on this dam. Investigations and results regarding parameter variations and assessment criteria for 3D models of concrete dams have already been published in [11], with the focus on reducing the parameter space and finding suitable criteria for the reliability analysis. Nevertheless, the following sections in this paper are mostly based on the aforementioned publication [11] for clarification purposes. The main goal of the investigation discussed in this paper is to reduce to amount of needed simulations for the reliability analysis to determine the exceedance probabilities and finding/evaluating suitable assessment criteria.

2. GENERAL INFORMATION

The investigations are based on a three-dimensional finite element model, which takes the loads and resistances into account as realistically as possible. The static and transient thermal analyses are carried out by using nonlinear material laws for the dam (masonry) and brittle rock subsoil, considering the seasonal instationary temperature fields and the load-dependent pore water pressures in the dam body. Additionally, the existing sealing and drainage elements as well as the nature of the rock subsoil are considered.

The investigation of the dam in [11] dealed with the following topics:

- Calibration and verification of the calculation model against measurement results,
- Stability assessment using the EC-compliant safety concept presented in [1] on the basis of partial safety factors,
- Basic studies on the behavior of the dam,
- reliability of the results and main impact factors,
- Stochastic investigations to assess the probability of failure

The gathered knowledge from these topics are the basis of the ongoing investigations.

All simulations are carried out using the finite element program ANSYS®, the elastoplastic material model library multiPlas [10] for ANSYS and the software for stochastic analysis ANSYS optiSLang® [9].

3. NONLINEAR FINITE ELEMENT MODEL

For the nonlinear simulations a 3D model of the dam and the foundation is created. The model has a width of 768 m, a length of 515 m and a height of 218 m. The FE model is shown in Fig. 1.

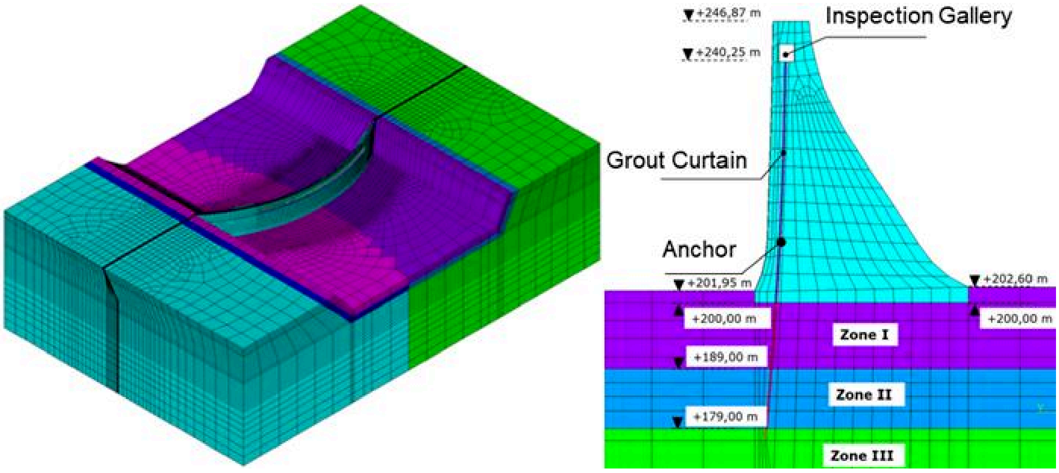


Fig. 1
3D FE-model of the dam and the dam section

The subsoil model is based on the data in [2], [3] and [5]. In total, three zones of different permeability in the vertical direction are considered (see Figure 2). Clay slate is found on the right slope according to [2]. On the left slope, greywacke with clay slate interlinings are found.

A grout curtain is installed and extends to a depth of +177.00 m a.s.l. in the region of the clay ridge and on both sides of the clay ridge to a depth of +191.00 m a.s.l.. 104 anchors stabilize the dam in the middle area. Each anchor contains 34 strands. The cross-sectional area of each strand is 150 mm². The anchor force is 4500 kN/anchor. 52 anchors reach into a depth of +167.0 m and 52 into +172.0 m. The grout length of the anchor for transmitting forces into the rock is 10 m each.

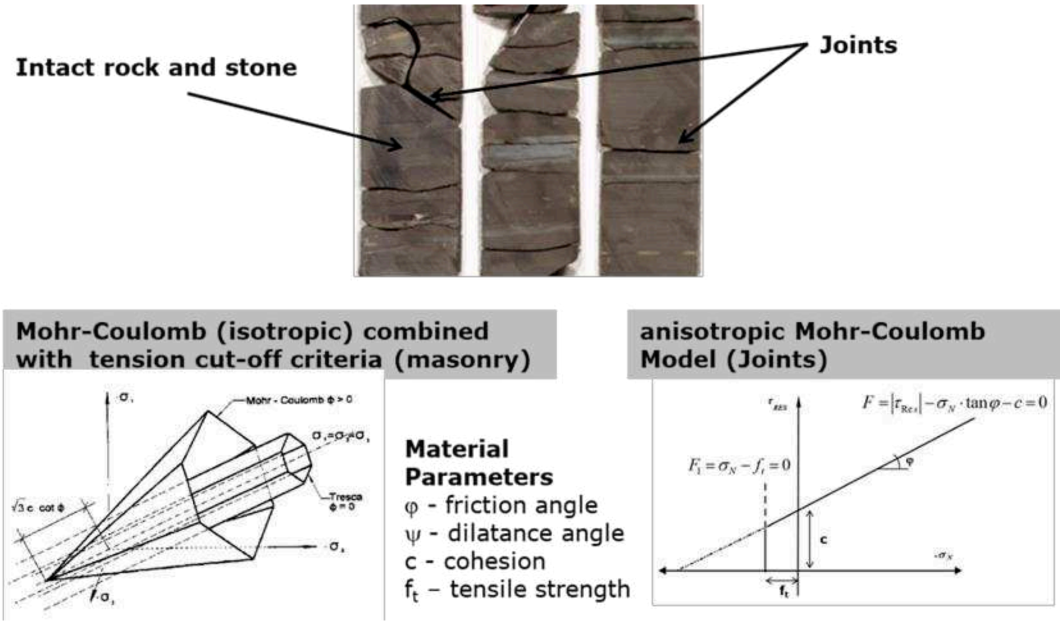


Fig. 2
Constitutive models used for the masonry dam, the intact rock and the joints

The nonlinear behavior of the masonry and the fissured rock subsoil is simulated using isotropic and anisotropic elastoplastic Mohr-Coulomb material models with tensile stress limitation. The position and orientation of the separating surface layers are also considered in the constitutive models. Virtual horizontal separation surfaces are taken in account to allow for stress free openings in vertical direction. Material parameters of the final calibration of the model can be found in Table 2. Fig. 2 illustrates the constitutive models used for the masonry dam, the intact rock and the joints. The final material properties from the calibrations are summarized in Table 2.

The boundary conditions are defined to prohibit the model to move in normal direction to the rock boundaries. The load history is taken into account in all load case combinations (LS) according to the composition in Table 1. The individual loads are multiplied by the corresponding partial safety factors from [1].

Table 1
Load steps of the nonlinear simulation

Loadstep	Action
LS1	Deadweight foundation (Initial Stress State)
LS2	Deadweight dam
LS3	Hydrostatic water pressure for defined water level
LS4	Hydrostatic water pressure at the level of anchor pre-stressing (241,605 m NN)
LS5	Anchor activation
LS6	Anchor pre-stressing
LS7	Hydrostatic water pressure for defined water level
LS8 f.	Additional varying loads according to Eurocode [1]

Non-stationary thermal finite element calculations are carried out for the determination of the temperature stresses in the dam. The external temperatures in the Hessen region are extracted from [7]. The water temperatures are taken into account in the thermal calculations as a function of time and water depth according to temperature data available at BAW (Federal Waterways Engineering and Research Institute).The 3D pore water pressure fields are calculated with a transient thermal analysis using a temperature-flow analogy.

4. MODEL CALIBRATION AND VERIFICATION

In order to increase the realistic proximity of the simulation model and thus to achieve a high quality of the stability tests, the simulation model is calibrated with deformation measurements of the dam. The measured deformation points are shown in Figure 3. Furthermore, pore water pressure and temperature measurements are to verify the hydraulic and thermal analyses.

Parameter identifications and sensitivity analyses are done to determine the dependencies between the model/material parameters and the response variables/measurements to be calibrated.

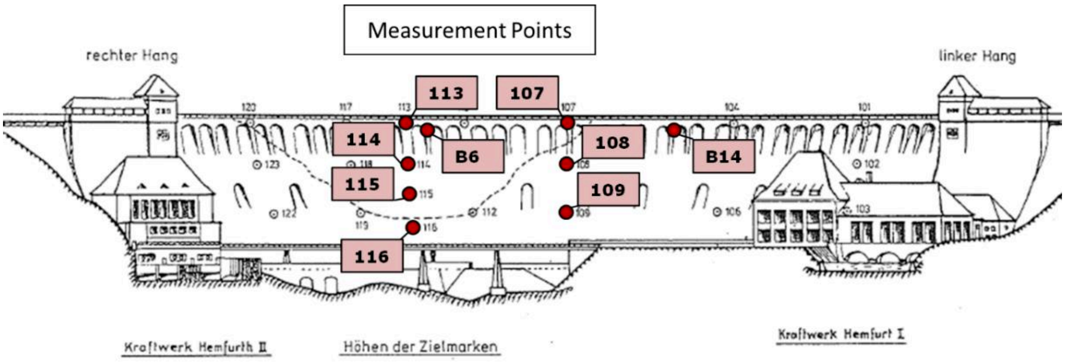


Fig. 3
Displacement measurement points used for calibration

The sensitivity analysis is carried out by means of variations-based correlation analysis in ANSYS optiSLang® [9]. All material parameters are varied as scattering inputs of the sensitivity analysis. The response variables are the radial relative displacements at the measurement points from Figure 3. 200 parameter combinations (designs) are calculated for the sensitivity analysis. Latin Hypercube sampling available in ANSYS optiSLang® [9] is used for sampling the 200 designs. In each design, a nonlinear load history calculation is simulated with the following load steps for calibration (LSC):

- LSC1 Activation of the dead weight in the foundation (Initial stress state)
- LSC2 Activation of the dead weight of the dam
- LSC3 Hydrostatic Water Pressure at 229,02 masl
- LSC4 Hydrostatic water pressure at minimum water level (220,00 masl)
- LSC5 Hydrostatic water pressure at maximum water level (244,95 masl)

The dam is simulated in the sensitivity analysis and model calibration without anchors and restoration measures, because the measured values of the deformation measurements originate from the time before the rehabilitation and the installation of the pre-stressed anchor.

The relevant input parameters (CoP values as a bar histogram) for the maximum water level (244.95 masl) and the minimum water level (220.00 masl) are calculated for each measuring point and the associated dependencies (anthill plots of the relevant input parameters vs. deformation). The CoP values are prognosis parameters and indicate how much the variance of the observed response variable (deformation at the measuring point) can be explained by the variation (or variation) of the respective input variable. Unimportant input parameters (whose scatterings are not correlated with the spread of the response variable) are automatically filtered out by ANSYS optiSLang® [9]. As the sensitivity analysis shows, the stiffnesses of the subsoil and of the masonry of the dam can be calibrated in particular by means of the deformation measurement values for the observed / measured water levels. It is also plausible that the stiffness of the masonry has a greater influence on the higher measuring points, whereas the deformation on the MP 116 is almost exclusively determined by the foundation stiffness. Fig. 5 shows the calculated and measured deformations. The black line indicates the measured values, gray lines indicate the spread of all designs and red is the best design Nr.186, which is determined by optimization and shows a very good agreement with the measured deformation values. As a result of the model calibration, a simulation model is developed which can easily and reasonably reconstruct the available measurements with regard to the deformations, temperatures and pore water pressures.

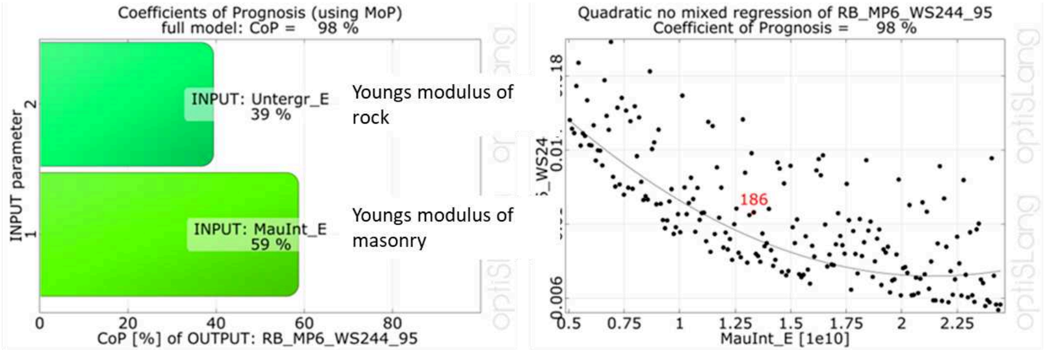


Fig. 4

Results of the sensitivity analysis for measurement point B6; left: Histogram of CoP; right: Anthill-Plot of the E-modulus of the dam (MauInt_E) vs. radial displacement at measurement point B6

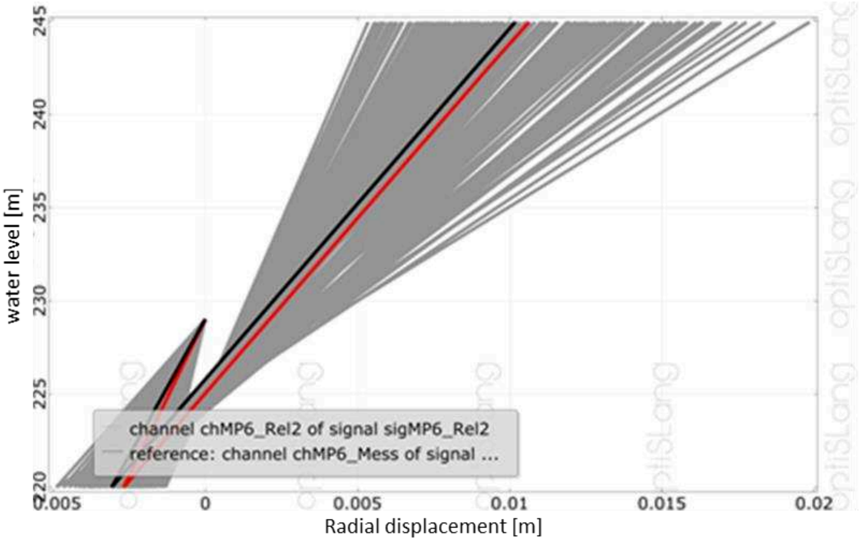


Fig. 5

Radial displacement of measurement point B6, Grey: Band width of all designs; Red: Best design Nr. 186; Black: Measurement

Table 2 summarizes the calibrated material and joint parameters for the dam and the foundation. Zones are depicted in Fig. 2.

Table 2
Calibrated material properties of the masonry and rock

	Dimension	Masonry	Intact Rock
Density	t/m³	2.2	2.72
E-Modul	N/mm²	11100	4697
Poisson ratio	-	0.25	0.257
Compressive strength	N/mm²	5	20
Friction angle	°	45	45
Cohesion	N/mm²	1.0355	4.14
Tensile strength	N/mm²	0.5	2
Residual friction angle	°	31.5	31.5
Residual cohesion	N/mm²	0.1036	0.4142
Residual tensile strength	N/mm²	0	0
Reference temperature	°C	10	8

5. STOCHASTIC ANALYSIS

Based on the experiences gathered from the stability studies and stochastic analysis from [11] new assessment criteria and more elaborated reliability analyses are carried out using the calibrated FE model.

The motivation for the stochastic analysis results from several questions. For example, a stochastic analysis can be used to circumvent contradictions arising from the use of partial safety factors in nonlinear analyses, where questions arise from whether it should be determined by a load-side increase or by a reduction of the resistance. Both approaches aren't without doubt possible in connection with nonlinear analyzes.

By means of a stochastic analysis, failure probabilities can also be determined in the case of nonlinear analyses when introducing load and resistance-side scatterings. This procedure is included in Eurocode EN 1990:2002 (Annex B and C). In a recent and ongoing cooperation between the BAW (Federal Waterways Engineering and Research Institute) and Dynardo, the example of this dam is worked out, including further fundamental investigations, to develop a procedure for practical projects.

The stochastic analysis consists of the following steps.

- Definition of the scattering of the input parameters.
- Generating the samples in ANSYS optiSLang® [9], various methods (Monte Carlo, Latin Hypercube, Directional Sampling, FORM, ...) are available for this purpose.
- Definition of evaluation criteria, e.g. Displacements in the abutment, Displacement gradients in the abutment, tilt safety - position of the resultant, sliding safety - principal shear strain, pressure failure -

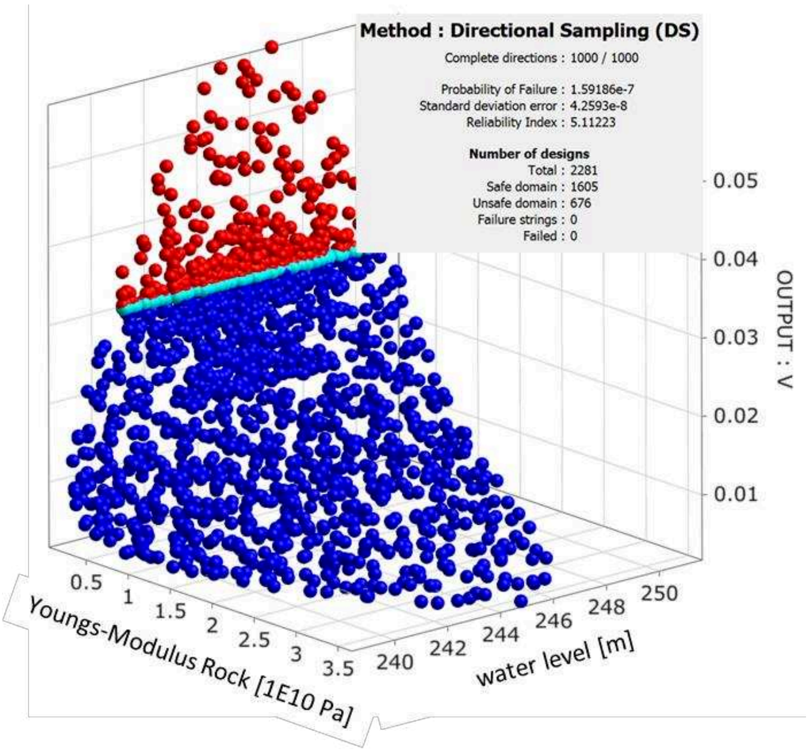
principal normal strain and risk of fracture in the grouting zone - max. plastic vertical strain, etc.

- Performing nonlinear analyses of all necessary designs defined by the sampling method.
- Evaluation and determination of the probability of failure

5.1. RESULTS OF THE STOCHASTIC ANALYSIS

In this investigation two reliability analyses by means of probabilities of failure are carried out. To determine the exceedance probabilities, an adaptive response surface method (ARSM) was used in combination with the First Order Reliability Method (FORM). For each reliability analysis, more than 600 designs were calculated in individual (here three) iteration steps. With each iteration step, new designs are created that are closer to the limit state. The approximation quality of the generated response surfaces is 99%.

The total displacement V (nodal mean value at the abutment) is used as the evaluation criteria. For the derivation of the limit values, limit load analyses were carried out (due to load increase and due to resistance reduction). Two threshold levels were derived for the rating criterion V, which are V_1 = 0.05 m (near system failure) and V_2 = 0.03 m (transition to non-linear system behavior)


```
Method : Directional Sampling (DS)
Complete directions : 1000 / 1000

Probability of Failure : 1.59186e-7
Standard deviation error : 4.2593e-8
Reliability Index : 5.11223

Number of designs
Total : 2281
Safe domain : 1605
Unsafe domain : 676
Failure strings : 0
Failed : 0
```

Fig. 7
Reliability analysis V_2, All Design points in the space of the most important parameters; red dots: V > 0.03 m; blue dots: below the limit of 0.03 m

The exceedance probability of the reliability analysis for the limit value of V_1 = 0.05 m gives a $P_{f(V\_1)} = 1.59 * 10^{-13}$; which corresponds to a reliability index $\beta_{(V\_1)} = 7.29$. The result of the reliability analysis for the limit value V_2 = 0.03 m is shown in Fig. 7. The determined exceedance probability is $P_{f(V\_2)} = 1.59*10^{-7}$; this corresponds to a reliability index $\beta_{(V\_2)} = 5.11$

As a result of the analyses, it can be stated that both probabilities are below the value of $P_f = 10^{-5}$, corresponding to reliability indexes above $\beta = 4.27$ (Reference period of 100 years). Thus, by using probabilistic analyses and procedures described in the report, a sufficient stability of the Eder dam can be confirmed and the safety margins beyond are quantified.

In addition to the calculation of the probability of failure, the influencing parameters which are decisive for the distribution of the response variable can be output both qualitatively and quantitatively in ANSYS optiSLang® [9]. This allows statements to be made as to which stray input variables (loads, resistances) are relevant for the failure of the dam.

6. ACKNOWLEDGEMENTS

The financial and technical support by BAW (Federal Waterways Engineering and Research Institute) is gratefully acknowledged.

REFERENCES

[1] FLEISCHER H., FRÖBISCH H.-J. 100 Jahre Edertalsperre – Untersuchungen zur Standsicherheit der Staumauer. *BAW Kolloquium Berechnungen und Analysen für bestehende Wasserbauwerke, Karlsruhe*, 2014.

[2] HESSISCHES LANDESAMT FÜR BODENFORSCHUNG Ingenieurgeologisches Gutachten. *Hessisches Landesamt für Bodenforschung 345 - 310/85 Hz/Str*, 1985.

[3] HESSISCHES LANDESAMT FÜR BODENFORSCHUNG Geologisches Ergänzungs-Gutachten. *Hessisches Landesamt für Bodenforschung 345 - 36/92 Hz/Bm*, 1992.

[4] EDERTALSPERRE Festschrift, Herausgegeben aus Anlaß der Wiederherstellung der Staumauer, Wasser- und Schiffahrtsverwaltung des Bundes, Wasser- und Schiffahrtsdirektion, Mitte Hannover, 1994.

[5] HOLTZ S. Die geologischen Verhältnisse [4]. 1994, Beitrag 3, S.24-25, Hannover.

[6] WITTKE W. Standsicherheitsberechnungen der Ederstaumauer nach der FE-Methode [4]. 1994, Beitrag 5, S.29-35, Hannover.

[7] TRY 2011 Aktualisierte und erweiterte Testreferenzjahre von Deutschland für mittlere, extreme und zukünftige Witterungsverhältnisse. 2011, Bundesamt für Bauwesen und Raumordnung (BBR) / Climate & Environment Consulting Potsdam GmbH / Deutscher Wetterdienst, Potsdam.

[8] WITTKE W. Felsmechanik, Grundlagen für wirtschaftliches Bauen im Fels. 1984, Springer-Verlag, Berlin, Heidelberg, New York, Tokyo.

[9] OPTISLANG MANUAL The optimizing Structural Language version 6.2.1. 2017, DYNARDO GmbH, Weimar, www.dynardo.de.

[10] MULTIPLAS MANUAL Elastoplastic Material Models for ANSYS - General Multisurface Plasticity. 2017 DYNARDO GmbH, Weimar, www.dynardo.de.

[11] SCHLEGEL R., GOLDGRUBER M., MROZEK M., FLEISCHER H. Investigation of the Reliability of Dams with Stochastic Finite Element Methods. *Proceedings of the 14th ICOLD International Benchmark Workshop on Numerical Analysis of Dams, 2018.*

SUMMARY

The analysis of failure probabilities is an important element of risk assessment in dam management. This investigation is illustrating probability of failure calculations of the Eder dam, an old gravity dam in Germany, by means of a parameterized and fully nonlinear 3D-finite element model of the dam and the foundation. The model is calibrated based on measurements (thermal, hydraulic and mechanical) with the software optiSLang®. Therefore, sensitivity analysis with stochastic latin hypercube sampling is performed using a total of 200 designs (parameter combinations) with varying material parameters of the dam and the foundation. For the stochastic analysis of the dam, distribution functions for all relevant effects and resistances, e.g. flood events, are defined. After all, the evaluation of the stochastic analysis is done again with optiSLang®, which is capable to directly yield the failure probability P_f for the specified assessment criteria. Additionally, input parameters influencing the failure probability the most can be indicated quantitatively and qualitatively. Two reliability analyses by means of probabilities of failure are carried out. To determine the exceedance probabilities, an adaptive response surface method (ARSM) was used in combination with the First Order Reliability Method (FORM) with several hundred simulations each. As a result of the analyses, it can be stated that both failure probabilities are below the value of $P_f = 10^{-5}$, corresponding to reliability indexes above $\beta = 4.27$ (Reference period of 100 years). Thus, by using probabilistic analyses and procedures described in the report, a sufficient stability of the Eder dam can be confirmed and the safety margins beyond are quantified.

Keywords: Finite Element Method, Gravity Dam, Safety of Dams, Stochastical Method