Analysis of Dams Pursuant to E-DIN 19700 Using ANSYS

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Summary

All standard safety analyses for existing dams must be tested and in some cases redone on the basis of the draft of E-DIN 19700. In the future, these analyses of existing or planned dams must be carried out with regard to coupled mechanical/ thermal/ hydraulic and structural analysis with modern numerical calculation programs. A typical starting point for many existing structures in Germany is that the analyses that are now required cannot be successfully performed with the simplified methods that have been used. In order to be able to demonstrate the required safety coefficient, available load reserves for existing structures must be tapped. The effectiveness of the ANSYS program system in carrying out analyses according to E-DIN 19700 will be examined on the basis of the example of the Lehnmühle Dam.

Keywords

Dams, E-DIN 19700, load capacity, serviceability, durability, elasto-plastic material behavior, earthquake calculation, stationary fluid flow calculations, transient temperature field calculations

0. Introduction

With the draft of E-DIN 19700, some new analyses are required for existing dams. In the future, analyses of existing or planned structures with high security requirements may be carried out using suitable powerful numerical calculation programs. Above all, the required analyses of loading from flow-through and earthquakes often cannot be carried out successfully with the conventional simplified analysis process.

The underlying safety concept provides for an analysis that shows a sufficient safety margin of the resistance of the structures compared with possible stresses during their period of use. For safety-relevant structures, such as dams, extremely low failure probabilities (10^{-6}) are strived for. Therefore, the norms demand high safety margins and assume extreme loads.

In addition to planning new structures, existing structures must also be analyzed regularly for load capacity, serviceability, and durability, and carried out anew if necessary. In Saxony alone, more than 100 dams are affected. It is typical for historical structures that the increased safety margin can no longer be generated with the currently used simplified analysis methods. One reason for this is that with the simplified analysis methods, the resistance of the structures must be estimated ***conservatively***, that is, often they are lower than the actual values. High safety reserves on all sides, however, lead to a situation where many structures that have existed for a long time cannot be shown to meet the current requirements for safety margins. In such cases, is it necessary and inevitable that expensive renovations to strengthen the structures be carried out?

With the help of modern calculation processes, stresses and resistance can be registered more realistically. This makes it possible to tap load reserves and calculate given safety margins more realistically. Recalculations show that, in particular, three-dimensional modeling, realistic load calculation, and realistic materials models in part make considerable load reserves accessible or show the simplified analysis process for load behavior unrealistically [7]. A responsible mode of operation demands that all assumptions remain conservative when load reserves are tapped. In particular, it must be guaranteed that resistance is not overestimated and loads are not underestimated during the idealization of numerical calculation methods. The calculation engineer must have intellectual control over the calculation model and be able to verify the results of the calculation at all times. Otherwise there is a danger of producing so-called “colorful images.“ These result in high demands on numerical calculation programs [8]. Calculation programs should have or allow the following:

- high quality assurance; a high level of verification
- a sufficiently good library of suitable non-linear material models
- no limits to the modeling of geometry; full 3-D functionality
- the ability to perform fluid flow and temperature field calculations
- the ability to perform non-linear load-capacity analysis and
- earthquake calculations using response spectral methods as well as transient earthquake analysis

The effectiveness of the ANSYS program system in carrying out analyses will be examined based on the example of the Lehnmühle Dam.

1. Stability analysis of the Lehnmühle Dam pursuant to E-DIN 19700

The Lehnmühle Dam is a gravity dam made out of quarry stone, which was built in the Osterzgebirge region of Saxony between 1926 and 1931. The dam is 50.6 meters high and has a crown length of 418 meters. This dam, along with the Klingenberg Dam, protects the people living near the Wilder Weißeritz river and Saxony's capital, Dresden, from flooding and provides them with drinking water. Renovation work was carried out in stages between 1975 and the 1990s. The Lehnmühle Dam survived the extreme flooding of August 2002 without any damage at all.

Fig. 1 Aerial photograph of the Lehnmühle Dam

1.1 Modeling

The Lehnmühle Dam has a straight dam axis; we are assuming isotropic behavior in the subterranean region of jointed rock. Therefore the dam is analyzed in unfavorable sections in a 2½-D model. Fig. 2 shows the modeling of the dam in measuring profile 5.

All parts of the dam that are relevant for standard safety considerations (quarry stone wall, faced brickwork, excavation, drainage, foundation) were modeled.

A sufficiently large model of the surrounding jointed rock was created and suitable fare field boundary conditions were selected for all calculations that were conducted (nonlinear static calculation, temperature calculation, fluid flow calculation, transient analysis). Isoparametric 3-dimensional finite elements with extra shape functions (for suppressing undesirable locking effects) were used [1]. Modeling, boundary conditions and the finite element discretisation were verified.

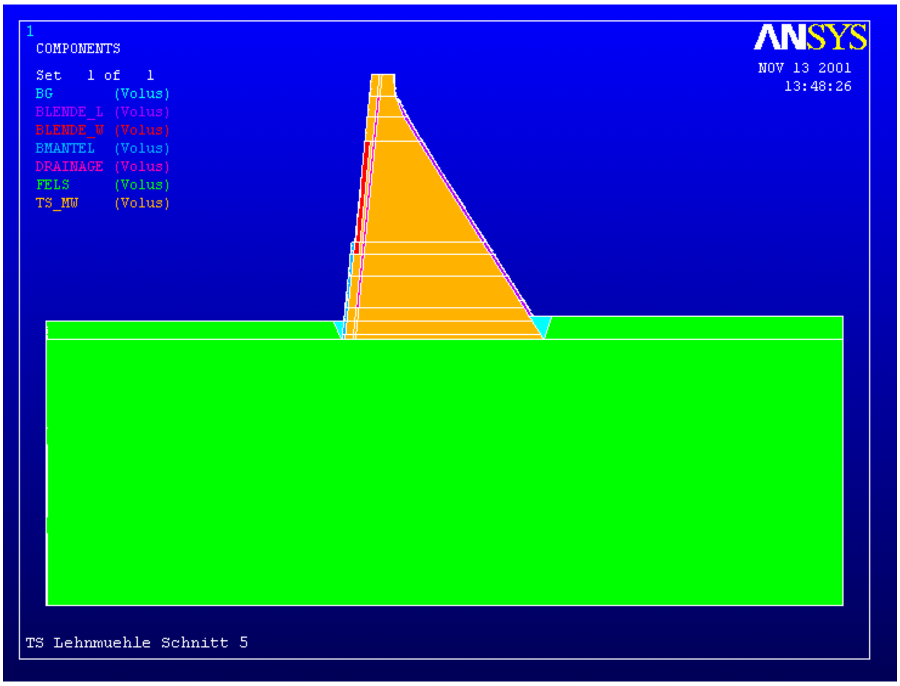

Fig. 2 Measuring profile 5 – complete model

1.2 Realistic determination of resistance

In order to realistically calculate resistance, elasto-plastic models are used for both the dam and the jointed rock. CAD-FEM has expanded ANSYS's necessary capacity for this and integrated a Multiplas [4] elasto-plastic material library for civil engineering and geomechanics into ANSYS. The high efficiency and effectiveness of this in processing complex elasto-plastic material models and also the assurance of consistency and convergence up into the failure status have been proved successfully many times [7, 6].

Following the verification [6] of suitable material models, Mohr-Coulomb material model with tensile cut off was selected for the analyses of the Lehnmühle Dam. Because no definite assertions could be made regarding the situation of the joints for the quarry stone brickwork, no anisotropic failure criteria were assumed for the brickwork. The shear strength was limited isotropically and an isotropic tensile strength limit was imposed. Because the jointed rock in question can be characterized as „healthy, gneiss with hardly any joints and no areas of weakness," isotropic Mohr-Coulomb material model is also assumed for the jointed rock. It is noted here that severely anisotropic non-linearities in the jointed rock have a strong effect on the stability behaviour as well as on the validity of the 2½-D geometric model, even in case of dams with a straight dam axis [7].

The assumptions regarding elasto-plastic material parameters strongly influence the dam's load behavior. While the quarry-stone wall has relatively high elasto-plastic resistance for the shear stability, material parameters for the faced brickwork and the jointed rock represent conservative estimated values. The very low cohesion of the facing means that the load-bearing effect of the subsequent strengthening measures is expected to be very small. The rock certainly has greater shear stability.

Regarding to DIN norms no tensile stress was allowed in the dam or the jointed rock. In particular, the assumption that no tensile stress at all could be allowed in the entire dam or the jointed rock is once again a very conservative assumption.

But for all of that it could be shown in the elasto-plastic analyses that the bearing stability of the dam was not being exceeded. As expected, considerable tensile strength loads appeared in the elastic comparison calculations. It could be shown that the tension stress (even when the tensile strength is assumed to be zero) was besieged successfully in all loading cases. The earthquake load case could be verified with a tolerable tensile stress of 200 KN/m^2. Tensile stresses of 200 KN/m^2 are a thoroughly realistic tensile strength for quarry-stone walls, even for quasi static loading [5].

	Friction angle in °	Dilatancy angle in °	Cohesion KN/m2	Tensile Strength KN/m2
Stonework, BG	45	10	600	1*
Rock	45	10	600	1
Earth dam	18	10	1	1
Protective concrete coating	45	10	100	1
Water-side diaphragm	45	10	100	1
Air-side diaphragm	45	10	100	1

Table 1: Elasto-plastic parameter values for Mohr-Coulomb WZA
*in the earthquake load case, 200 KN/m^2 tensile strength was allowed

1.2 Analysis plan

Non-linear, quasi-static load-history calculations were carried out to analyze the dam. The load history was allowed for in all load cases in the following ways:

Load step 1: Calculation of the empty reservoir without additional loads (impact of the reservoir's own weight and the stationary load from the water pressure fields as a result of ground water level)

Load step 2: Calculation of the accumulation (impact of the reservoir water load and the stationary load from the water pressure fields for the current water level) plus all additional loading from temperature of earthquakes.

In the safety concept in E-DIN 19700, Part 11, the maintenance of safety coefficients in terms of bearing failure is demanded for load-safety analysis. Basically, safety coefficients can be implemented on the load or resistance side in non-linear calculations. The safety coefficients demanded for the friction failure were seen as attenuating factors for the friction angle and the cohesion in the elasto-plastic calculations.

In the safety concept in E-DIN 19700, different safety coefficients are given for friction and compression pressure failure. Spatial elasto-plastic material models usually limit the total allowable stress space and different safety factors in a load-capacity calculation cannot be accepted without conflict. When the material parameters that describe the yield surface (cover surface of the allowable stress) are attenuated, an explicit separation between friction and compression failure is often no longer possible. In this way the material parameters of the Mohr-Coulomb shear fracture criteria (friction angle, cohesion) limit the compression pressure area as well and can be recalculated as compression stability. It was shown that shear stability has a dominant influence on the material model for the Lehnmühle Dam. Therefore the safety factors for compression was not explicitly included in the calculations.

	Safety coefficient trust bearing state I	Safety coefficient trust bearing state II	Safety coefficient trust bearing state III
Stonework, BG	1.5	1.3	1.2
Rock	2.0	1.5	1.2
Earth dam	1.0	1.0	1.0
Protective concrete coating	1.5	1.3	1.2
Water-side diaphragm	1.5	1.3	1.2
Air-side diaphragm	1.5	1.3	1.2

Table 2: Safety coefficients for the shear stability for different trust bearing state bearing

An important analysis criterion for elasto-plastic load-capacity calculations is that a state of equilibrium can be reached. Then sufficient stability is reached with regard to the safety coefficients that are demanded. If the allowable stress is exceeded, this excessive stress is identified with the help of the elasto-plastic material laws and force within the structure is redistributed through plastic deformation. If the plastic imbalancing forces of the structure can be redistributed, sufficient force-redistribution power is verified.

In the analyses, the plastic deformation intensity and the plastic activity are assessed. The plastic deformation intensity is a direction-independent measurement of the plastic deformation. The plastic activity shows which areas are active in a plastic sense in the state of equilibrium. We would like to point out that long-range plastic activities do not inevitably mean that the structure is failing. In some load cases, very long-range plastic activities were observed in the dam, but a state of equilibrium was achieved with little plastic strains and moderate increases in the total displacement nonetheless. Plastic activity means that the state of the tension lies in the yield surface, and loads in explicit directions can no longer be accommodated. If this limited capacity to further tolerate loads leads to failure, the plastic comparative expansion and the global distortion increase significantly or the disequilibrium forces can no longer be redistributed. In this case, once again, a distinction can be made between local and global failure.

The following are indicators of local failure of the dam, or local insufficient force-redistribution capability (e.g., failure of a facing):

- Global disequilibrium forces can no longer be redistributed (a convergence of the numerical calculation is not achieved)
- Locally there is major plastic strain
- Plastic activities are locally active
- Maximal deformations increase heavily on a local basis only

The following are indicators of global failure of the dam, or global insufficient force-redistribution capability:

- Global disequilibrium forces can no longer be redistributed (a convergence of the numerical calculation is not achieved)
- There is long-range major plastic strain
- At least one persistent band of plastic activity (from the water side of the dam to the air side of it) can be identified or almost the entire dam is plastically active

1.3 Assessment of realistic load conditions

In order to determine load-capacity reserves, it is very important to have a sufficiently detailed geometry model, a material model that is close to reality, a realistic assessment of loading from fluid flow, temperature loading, and earthquakes. In doing so, the mechanical strain of temperature loading as well as the force fields resulting from fluid flows and earthquakes are transferred directly within ANSYS and then applied in the non-linear mechanical load-history calculations.

In E-DIN 19700, the probabilities of occurrence of the various stresses and the thrust-bearing states are taken into account and the analysis is defined for numerous load-case combinations with the appropriate thrust-bearing states and load-case measurements. In total, up to 12 load cases are analyzed per profile [6].

1.3.1 Loading from fluid flow

The fluid flow calculations are carried out as stationary temperature field calculations. In doing so, the water pressure replaces the degree of freedom of temperature and the temperature conductivity is replaced by the permeability. For all boundaries the stationary water pressure is defined as boundary condition. When defining water pressure for the far field, a depth-dependent water pressure is assumed. With the temperature procedure, the water pressure fields of a stationary fluid flow are calculated. Note that with this procedure, no exact saturation line can be determined in the dam as a result of missing gravitation effects and the assumed saturation line in the dam is unrealistic high. This can be corrected with explicit specification of the saturation line.

As for the permeability of the bedrock, only estimated values were known from the bibliography. Because uplift measurements in the dam sole were available, the permeability of the jointed rock and the quarry stone wall were identified based on the measurement results. This ensures that in the stationary fluid flow calculations with the selected idealization, the actual integral flow force in the dam can be calculated with a very good approximation.

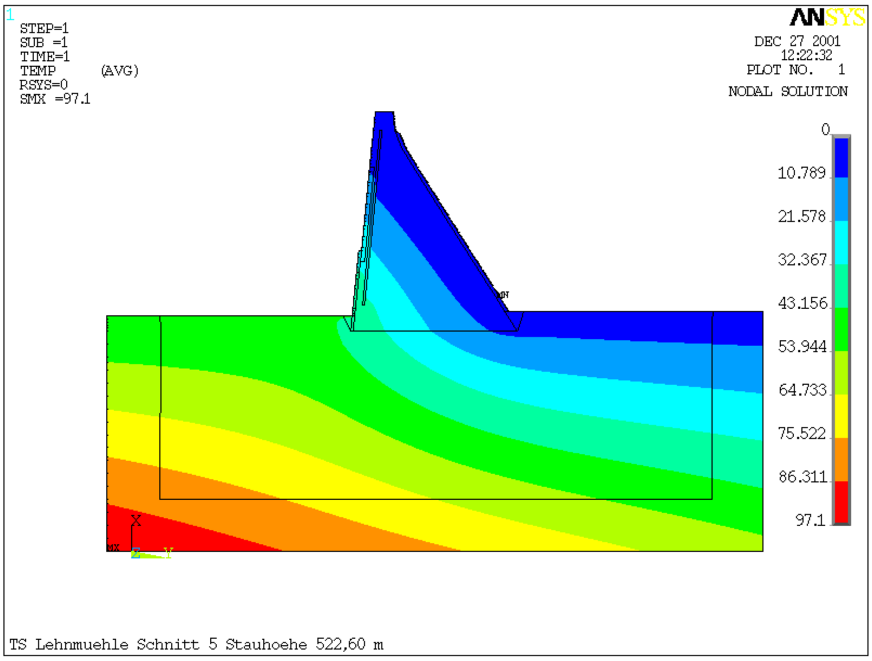

Fig. 3 Water pressure field [meter water column] operational water level with effective drainage

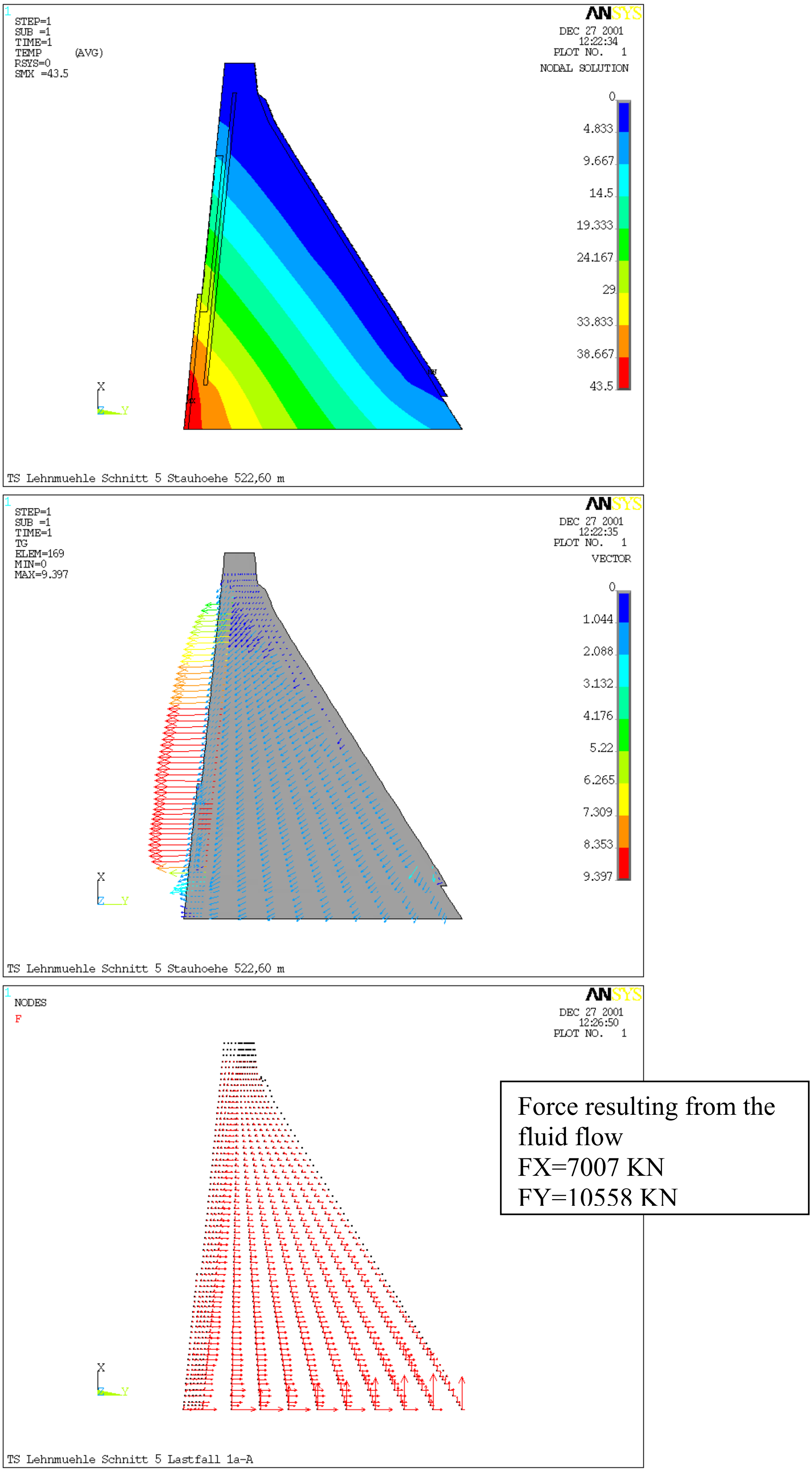

Fig. 4 Water pressure field in the dam, gradients of the water pressure distribution, and resulting current force in cases of partially effective drainage

The fluid flow calculations were carried out for different prescribed water levels. It was assumed that the quarry stone wall would be flowed through completely and the drainage would be only partially or not at all effective. These unfavorable assumptions ensure the conservative character of the load calculation.

From the stationary water pressure fields, the loads are calculated as current force. Similar to DVWK bulletin 242 [3], the current forces are calculated out of the gradients of the potential distribution. Because the water pressure (and not the stand pipe levels / piezometric head) is calculated in the potential field, the uplift forces (reduction of the weight of bodies in water) are included in the resulting current forces.

1.3.2 Temperature loading

Forced loading from temperature can lead to considerable stresses for massive structures. Typically, in structures, stresses from temperature are estimated over a temperature difference of approximately 20 Kelvin from the reference temperature of approximately 10°C. This kind of temperature fluctuation is completely realistic on the surface. But as a temperature difference for the entire structure, this often results in unrealistically high loads. In order to determine the temperature stresses more realistically, transient calculations of temperatures over a whole year were carried out. In doing so, the depth-dependent water-temperature fluctuations in the reservoir and also a constant fare field temperature and the air temperatures were used as boundary conditions. Under the assumption that the temperature fields with the largest crown displacements are unfavorable for the global load-capacity analysis, the standard temperature fields for rarely occurring temperatures in winter and summer were identified in transient mechanical thermal coupled calculations.

Because it can be assumed that only temperature differences to the reference temperature lead to forced loads, the reference temperature fields were removed from the unfavorable temperature fields and the difference temperature fields in the measurement load cases were applied as temperature loading.

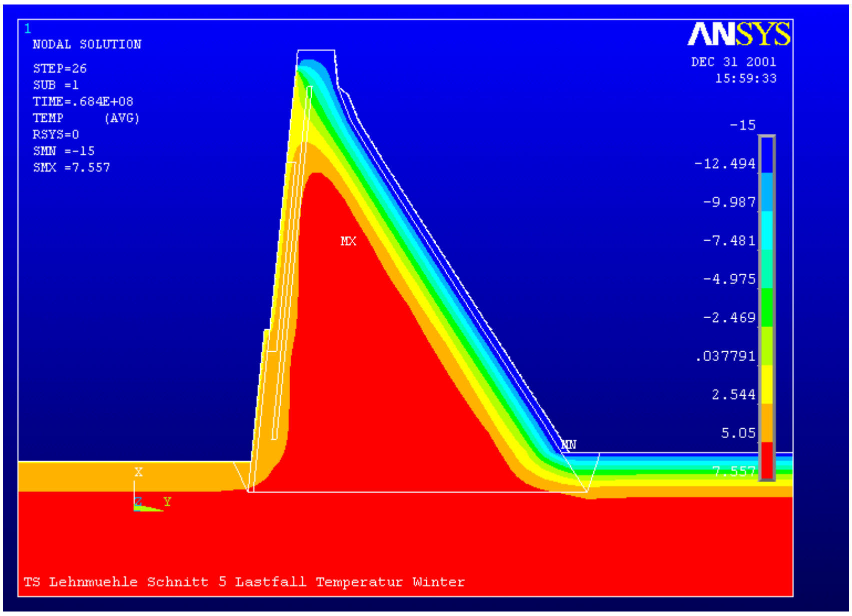

Fig. 5 Temperature field [in °C] with the greatest crown displacement (rare temperature occurrence in winter)

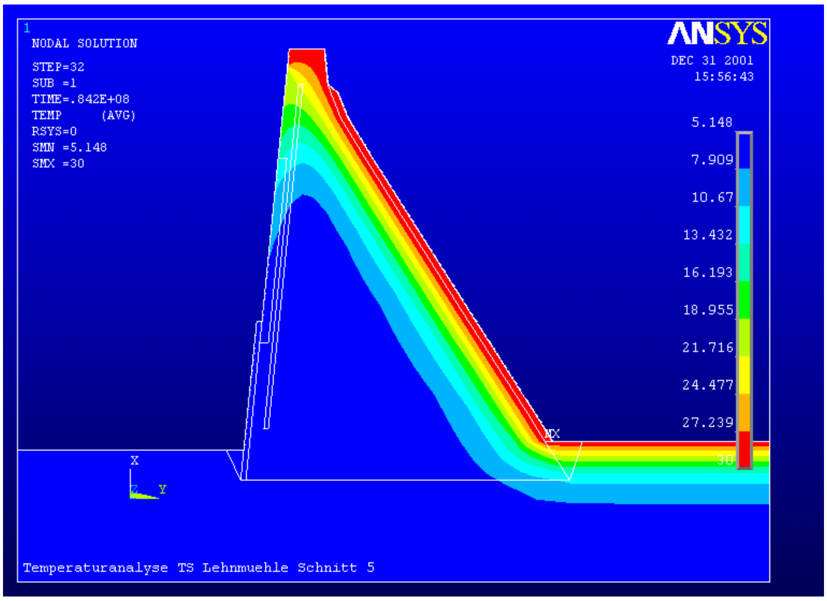

Fig. 6 Temperature field [in °C] with the greatest crown displacement (rare temperature occurrence in summer)

1.3.3 Loading from Earthquakes

Pursuant to E-DIN 19700, safety and operational earthquakes are to be analyzed. As a result of the slight difference in the corresponding thrust-bearing states, the safety earthquake load case was taken as the standard. Stresses from safety earthquakes were determined, according to recommendations from DVWK Merkblatt 242/1996 [3] with modal superposition in the response spectrum methodology.

The resonating water mass was applied according to [3] depth-dependent. In ANSYS the resonant water masses m_W for every element were determined and introduced on the water side of the dam as mass. According to [3] the first three natural frequencies (between five and ten Hertz) of the dam were used for the response spectrum methodology. With regard to the excitation spectrum and one percent modal damping, the modal load states were determined.

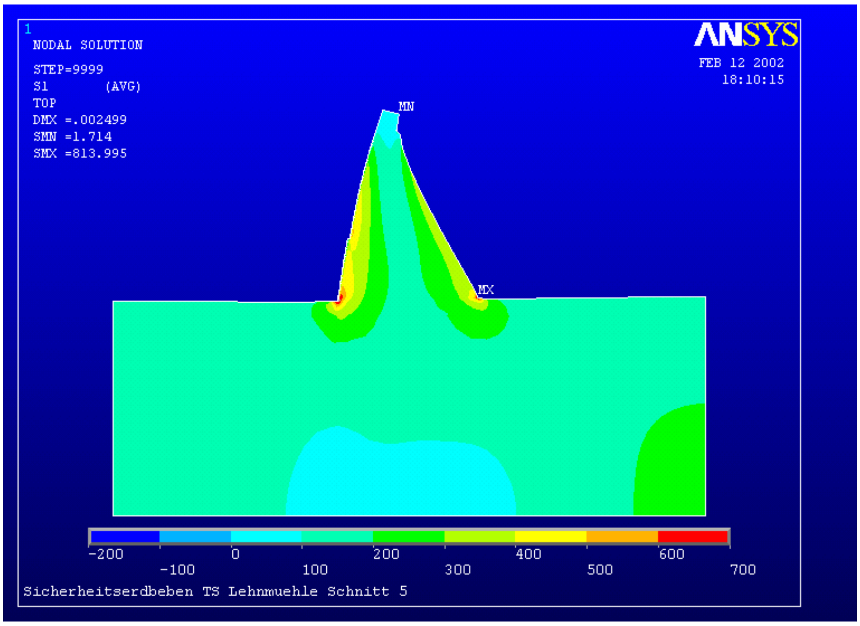

Fig. 7 Main tensile stresses [KN/m²] from the quadratic superposition of three modes

After [3], the forces and stresses of the individual modes can be overlaid quadratically. The resulting stress field from earthquake loading can be seen in Fig. 7. Note that using quadratic superposition all stress algebraic sign information and phase information is lost. In civil engineering, however, the stress algebraic sign information is extremely important because of the different strength values of tensile stress and compression stress. Exclusively local information about possible maximal stress values without statements regarding realistic stress algebraic sign and direction are not sufficient for load-capacity analyses with elasto-plastic redistribution in the entire system. Therefore the displacement and tension fields in the quadratic interaction do not appear to be suited for analyzing the structure's stress redistribution ability.

For a conservative estimate of possible loads as a result of earthquakes, the first 3 individual modes of the structure were overlaid in such a way that a maximal crown displacement in the direction of the valley results and the maximal tensile stresses on the water side. Under the assumption that the maximal possible tension stress fields are described adequately with the first three individual modes, an attempt is made to get a conservative estimate of possible tension stress fields through linear superposition.

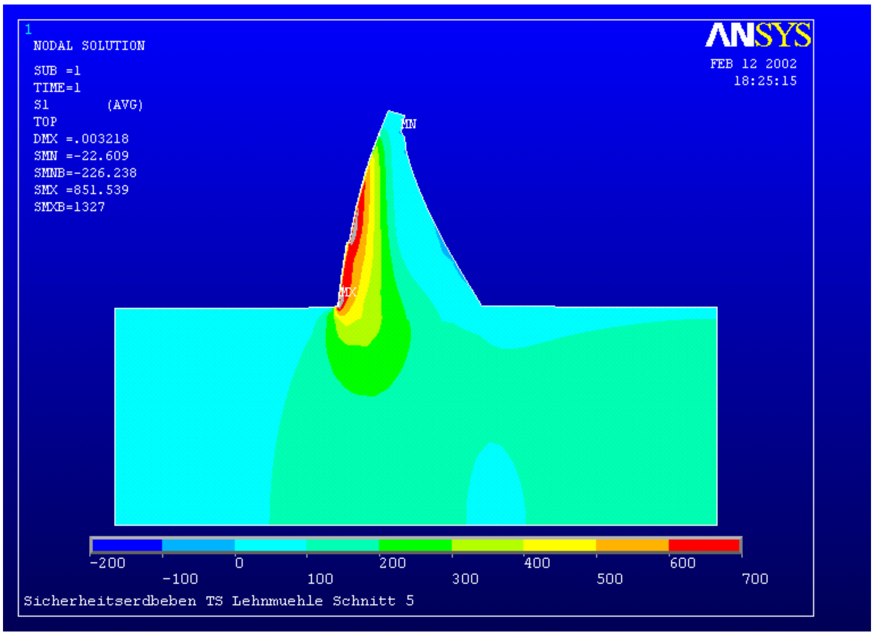

Fig. 8 Main tensile stresses [KN/m²] from the linear superposition of three modes

This assumption was verified with linear transient calculations of the earthquake. Time signals of ten seconds for horizontal acceleration, speed, and displacements of the strong quake phase were generated from the earthquake's load spectrum. Fig. 9 shows the speed function of the time signal. Fig. 10 shows good concordance of the energy content of the signal in the frequency range with the excitation spectrum of the specification.

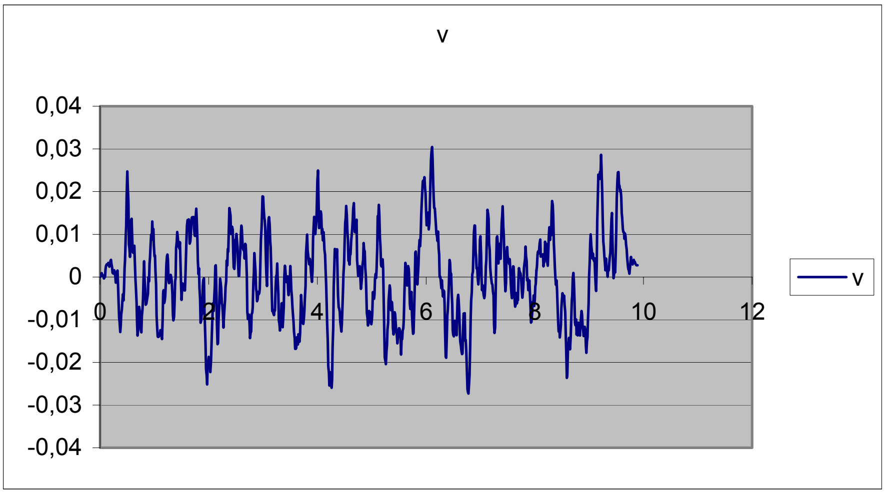

Fig. 9 Speed function of the strong quake phase in m/s

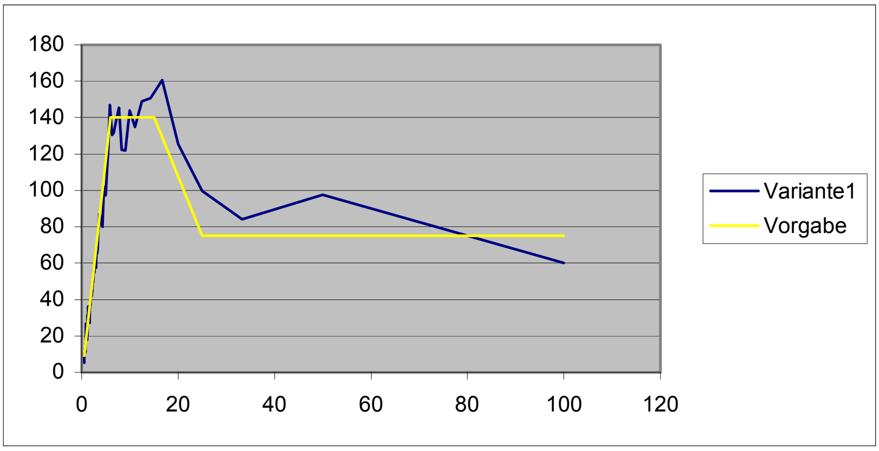

Fig. 10 Transformation of the acceleration signal in the frequency range and comparison with the excitation spectrum

In the transient calculation, Rayleigh damping is used that corresponds to the one percent modal damping of the answer spectrum process. In ANSYS the earthquake loads were applied as time-displacement curves in the fare field. Afterwards, the tension fields with the maximal main tension stresses on the water side were identified and compared with the tension fields of the linear superposition. The maximal main tension stress on the water side can be observed after approximately 4.5 seconds (Fig. 11). As expected, lower maximal values could be determined in the transient earthquake calculations (1330 ⇒ 1250 KN/m2).

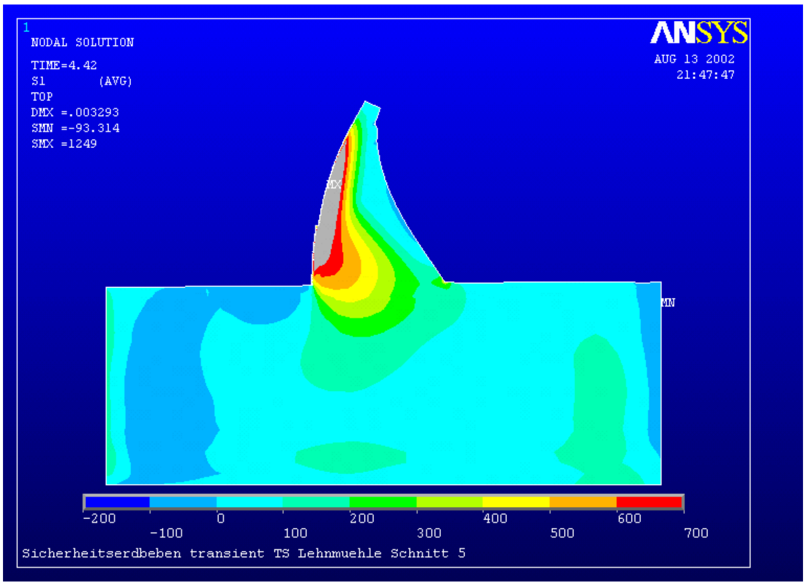

Fig. 11 Tension field of the maximal main tension load from the transient earthquake calculation

The tension distribution within the dam, however, demonstrates larger areas with high tensile stress in the transient calculations. The comparison shows that even a linearly unfavorable interaction of the first three modes is not conservative in the entire dam. Earthquake loads, e.g., from excitation of higher modes or unfavorable interactions can absolutely create locally more unfavorable tension stress fields.

As the recalculations of the earthquake loads with transient signals from the strong quake phase show, in case of doubt, transient non-linear calculations should be carried out to determine more realistic stress fields.

In analyzing the Lehnmühle Dam, the loads from the linear superposition (Fig. 8) were applied in the quasi-static load-history calculation, and the required safety could be proven under the assumption of a tensile strength of 200 KN/m^2. Alternatively, in ANSYS transient non-linear elasto-plastic calculations are also possible for analyzing the strong quake phase. Because of the stabilizing effects of the mass effects, there is a tendency for higher resistance to be expected of the dam in cases of transient elasto-plastic calculations of earthquake loads than in cases of quasi-static elasto-plastic analyses. Even if small increments are necessary for the release of the time signal and several hundred load steps with several thousand iterations can be expected in a transient non-linear calculation, the calculation time needed for it is still moderate and no longer an obstacle with current computer power.

1.4 Analysis of load-capacity

Of the numerous load cases, only the evaluation of the „Highest expected water level elevation Z_{H1} with drainage failure and unfavorable elasto-patristic parameters“ extreme load case will be shown here as an example. In order to get a gauge for the irreversible deformation, the results of the elasto-plastic calculations were also compared with the elastic comparison calculations.

The standard safety could be proven with the selected idealizations and specific values and with the required safety factors. States of equilibrium could be found for Load Step 1, the reservoir’s own weight (empty reservoir), and Load Step 2, highest expected water level elevation with ineffective drainage. The convergence criterion was one percent of the imbalance forces. The focus of the vertical tension was within the first core range of the dam sole.

The total displacement of the elasto-plastic calculation (17 mm Fig.12) is 5.8 mm (50 percent) more than the total displacement of the elastic comparison calculation (11 mm Fig. 12).

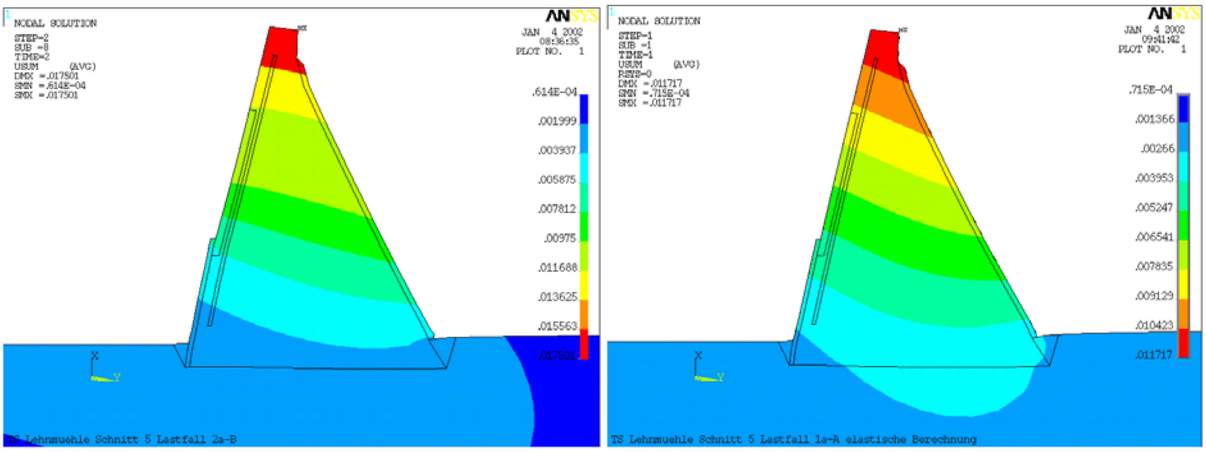

Fig. 12 Total displacement of the elasto-plastic calculations (left) and the elastic comparison calculations (right)

In this extreme load case, a clear increase in elasto-plastic redistribution could be observed in comparison with the operational load case. As a result of the assumption of drainage failure, the uplift forces, and thus the plastic deformation that results when tensile strength is exceeded (Fig. 13), grew sharply in comparison to the operational load cases, in particular on the water side.
Major plastic deformation that permeates the drainage zone to a great degree could be observed on the water side. In doing so, maximal plastic strain of up to 0.001 = 1mm/m appeared. Plastic strain of this magnitude leads to micro-cracks or very small opening of joints in the quarry-rock structure. According to E-DIN 19700, in areas with cracks, the maximum possible water pressure must be applied. In the water pressure calculations for the extreme load case, it could indeed be shown that assuming the complete failure of the drainage system in the areas with appreciable plastic strain made it so that the maximum possible water pressure was practically available. Therefore, we forewent an iterative crack-progress calculation with explicit definition of water pressure at the edges of the cracks.

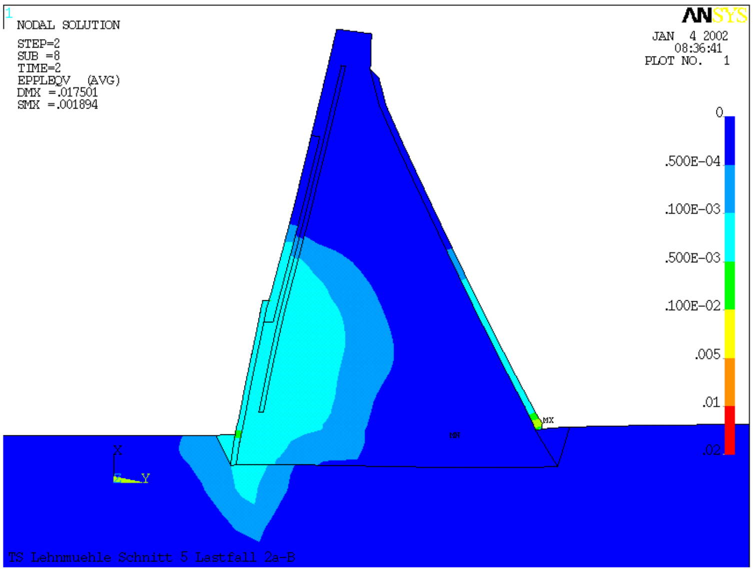

Fig. 13 Plastic strain

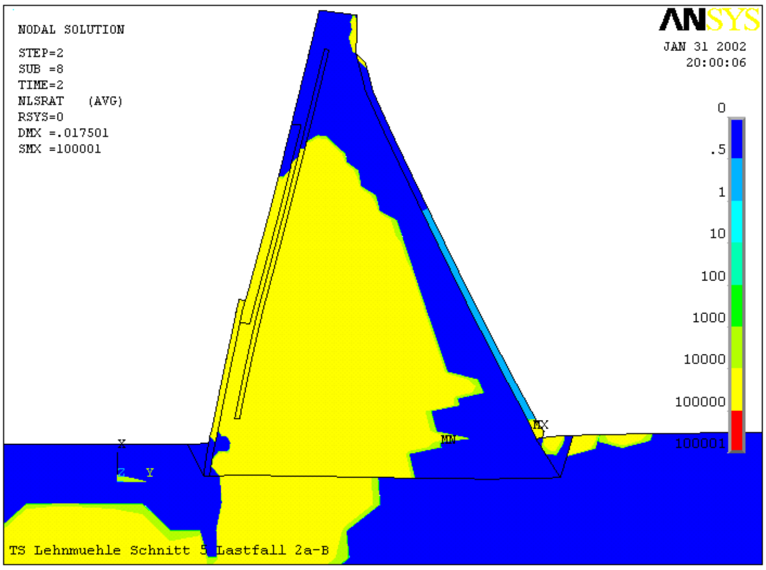

Fig. 14 Plastic activity (Yellow – tensile activity; Light blue –shear activity)

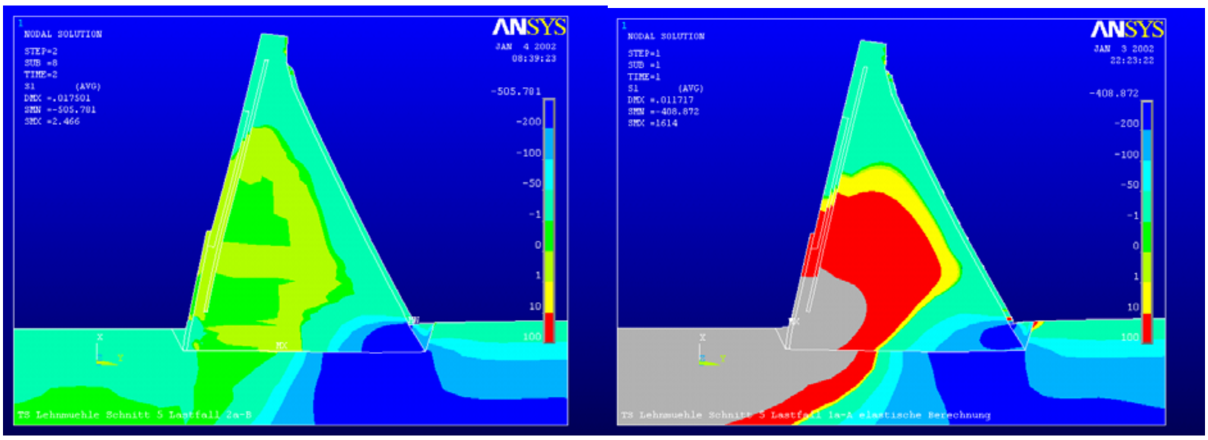

Fig. 15 Main tensile stresses [in KN/m²] for the elasto-plastic calculation (left) and the comparative elastic calculation (right)

The plastic activity (Fig. 14) extends along almost the entire dam in this extreme load case. The plastic activity that occurs there results almost entirely from the redistribution of considerable tensile loading (see Main tensile stresses of the comparative elastic calculation Fig. 15). Nevertheless, the long-range tensile stress overrun in the brickwork and rock could successfully be redistributed in the elasto-plastic calculation (Fig. 15). But it can be recognized with the long-range plastic strains and activities that the force-redistribution power of the dam in this extreme load case and assuming the required safety coefficients is almost exhausted.

2. Summary and outlook

The calculations for the stability analysis of the Lehnmühle Dam show that with the ANSYS program both the resistance (geometry, material behavior, interaction between the surrounding jointed rock and the dam) as well as the loads (temperature, fluid flow, earthquakes) can be described realistically. All analyses required pursuant to E-DIN 19700 could be carried out very well with quasi-static elasto-plastic load-history calculations. Important assumptions and idealizations could be verified successfully. CAD-FEM and DYNARDO successfully completed the necessary numerical and physical capability in recent years.

Above all, calculations regarding safety in case of an earthquake show that there is a need for discussion regarding the recommendations for carrying out analyses in E-DIN 19700 [2] and DVWK [3].

During the flooding catastrophe of August 2002, the catchment area of the Wilde Weißeritz was affected by extreme amounts of rainwater (the usual rainfall of four or five months within a period of 48 hours). The dam survived the more than 100-percent use of the flood discharge and thus the reaching of the maximum possible water level elevation without any damage. With the simplified analysis process, it was no longer possible to generate the stability analysis of the quarry stone wall for the maximum possible water level elevation. With above calculations, on the other hand, the stability analysis could be confirmed in a reproducible fashion. Thus it has been documented that through realistic provision for resistance and loads the available stability analysis can be analyzed with sufficient safety margins.

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