Numerical Analysis of Water Reservoir Dam - Prediction of Long Term Performance of Versetal Dam (Germany)

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ABSTRACT: In this study the long term settlement behaviour of a rock fill dam is predicted by means of numerical simulation (FEM). The measured ongoing deformations since operation of the Verse Dam lead to the conclusion, that a creep type process takes place. Thus a visco elastic plastic model was chosen for the simulation. In a sensitivity analysis the sensitivity of the model response (deformations) with respect to the material model parameters was analysed. The study included the strength parameters from the Mohr-Coulomb failure criterion, the basic stiffness parameters and some advanced parameters. The sensitivity analysis showed a significant influence of the stiffness and creep parameters on the mechanical behaviour of the dam. Using an optimisation tool and deformation measurements carried out and/ or horizontal measurements as reference values optimum set of parameter was derived. The optimum set of parameters was used to predict the deformations and the stability of the dam for the coming years.

Keywords: soil mechanics, soil model identification, soil parameter optimisation, inverse analysis, sensitivity analysis, prediction of long term behaviour, numerical simulation

1 INTRODUCTION

The Ruhrverband operates the Verse Dam and Reservoir with a storage volume of 33 Mio. m^3. The Verse Dam was built in the 30's of last century and is located in the Märkischer Kreis District, in the southeast of Lüdenscheid on the northwestern flank of the Ebbe hills (Germany). In addition to its main reservoir impounded by a rockfill dam, the Verse Reservoir includes a preliminary reservoir impounded by a dam. The water is primarily discharged from the reservoir through a power plant at the foot of the Verse Dam. Together with other reservoirs the Versetal Dam ensures to supply water to the Ruhr area and neighbouring areas. For routine the stability of the dam is calculated frequently using modified lamella (limit equilibrium) approach. Additionally extensive observations and measurements including horizontal as well as vertical deformations and water level fluctuations are carried out since the dam started operation in the 50's. Additional to the limit state calculations the relation between these measured deformations and the mobilization of factor of overall safety of the dam is of paramount interest for the upcoming years (e.g. for the next 10 years). The measurement points and the measurements are given in Figs. 1 and 2. The measurements include vertical as well as horizontal measurements, that are continuously taken along the dam crest, in the concrete core and on the dam at the air side since the operation of the dam in the 50's.

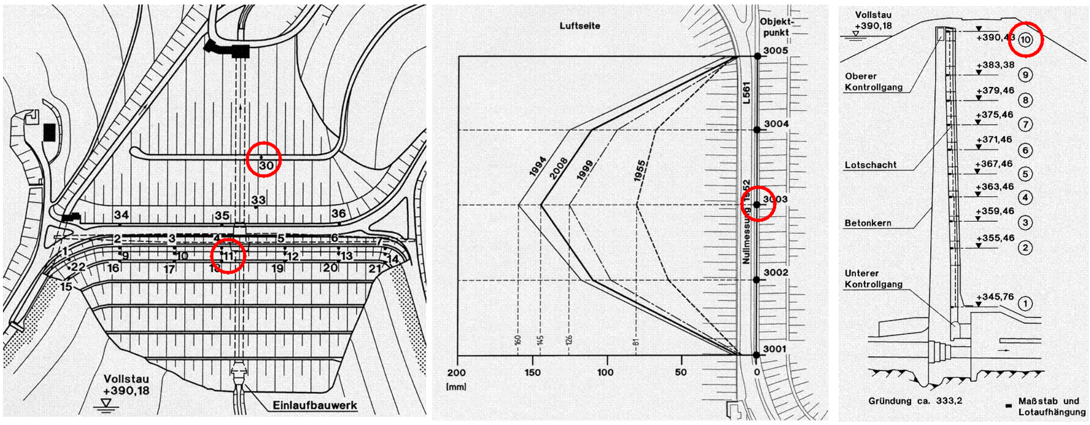

Figure 1. Measurement points

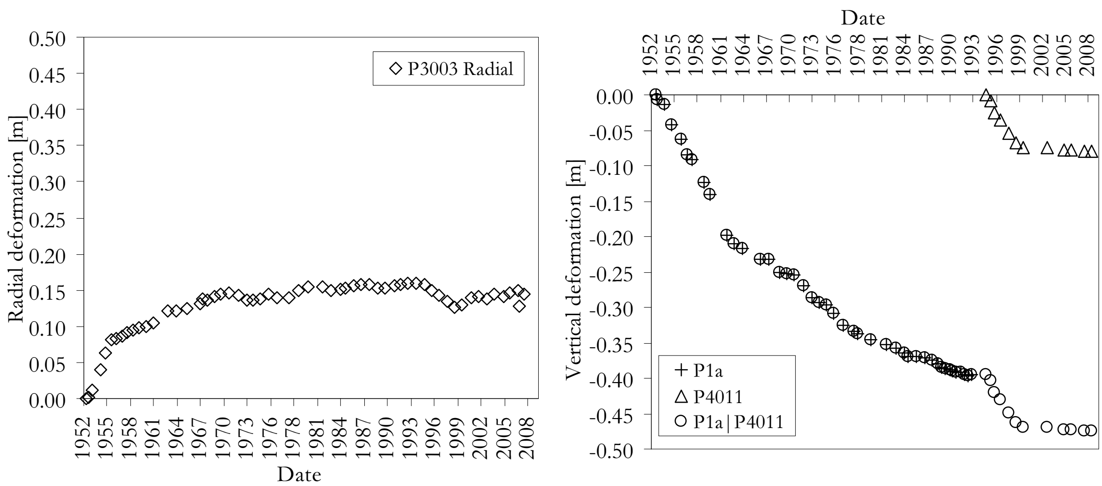

Figure 2. Measurements

2 NUMERICAL MODEL

In this study the long term deformation behaviour of the Versetal Dam is predicted by means of numerical simulation. Therefor the Finite Element Program PLAXIS was used. A multi step approach was followed in the following manner: In a first step a numerical model of the Versetal Dam was developed using Finite Element Method. The numerical model includes the geometry of the dam, material parameters, and initial as well as boundary conditions.

2.1 *Geometry of the Dam, Boundary and Initial Condition*

For the numerical simulation of the Versetal Dam a cross section in the middle of the dam was used. In the middle of the dam the maximum loadings as well as deformations due to increasing and decreasing water level were measured. The numerical model used for the FEM simulations and the generated mesh are given in Fig. 3. The width of the dam is at the bottom $\approx$ 290 m and at the top $\approx$ 16 m. The dam is $\approx$ 54 m in height. The dam is a rock fill type dam including a concrete core as well as a clay core, a sealing body and a rock fill and was founded on the bedrock, that is located below the soil of the valley.

The numerical simulation was carried out using 6-node triangular elements. The boundaries were fully fixed ($u_x = u_y = 0$) at the basement and roller conditions ($u_x = u_y = free$) were chosen for the vertical sides. Initial conditions (i.e. pore-water pressure and effective stress) were derived using a K_0-procedure (i.e. $K_0 = 1 - \sin\varphi$).

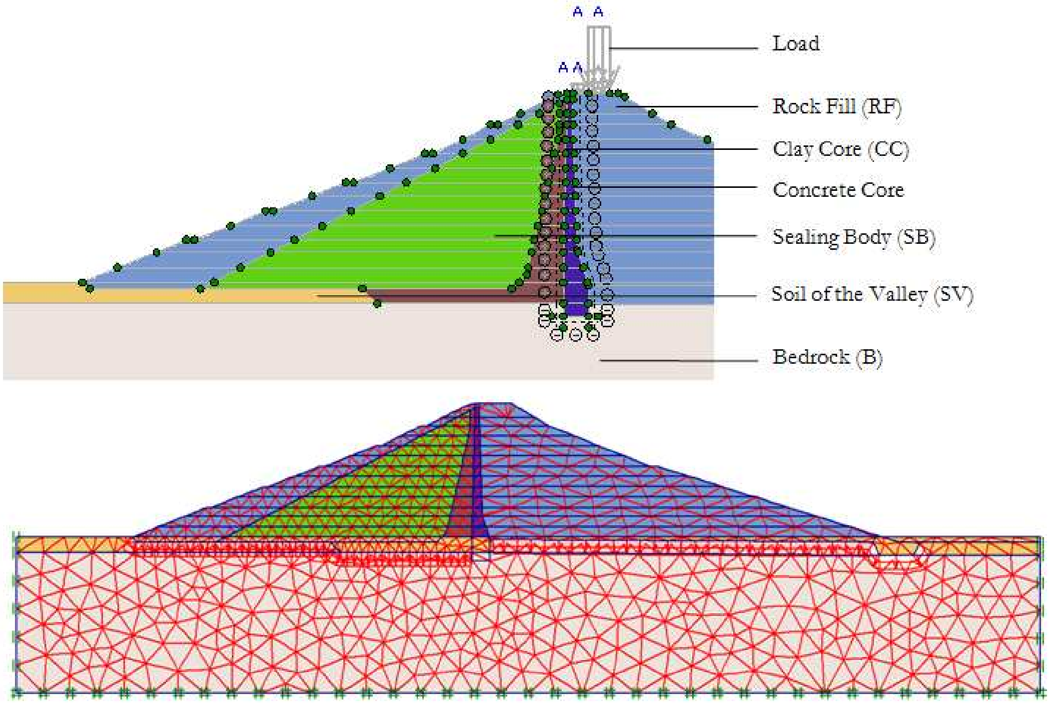

Figure 3. Model of Versetal Dam (top) and the generated mesh (bottom)

2.2 *Construction Phases*

The numerical simulation was carried out in several construction phases starting with the construction of the dam in 1938, the impounding of the dam in several phases as well as the period of the operation of the dam from 1955 up to 2009. The deformations of the dam and the bearing capacity were predicted for the upcoming 10 years. All phases were calculated as consolidation phases. In detail the construction phases are described below:

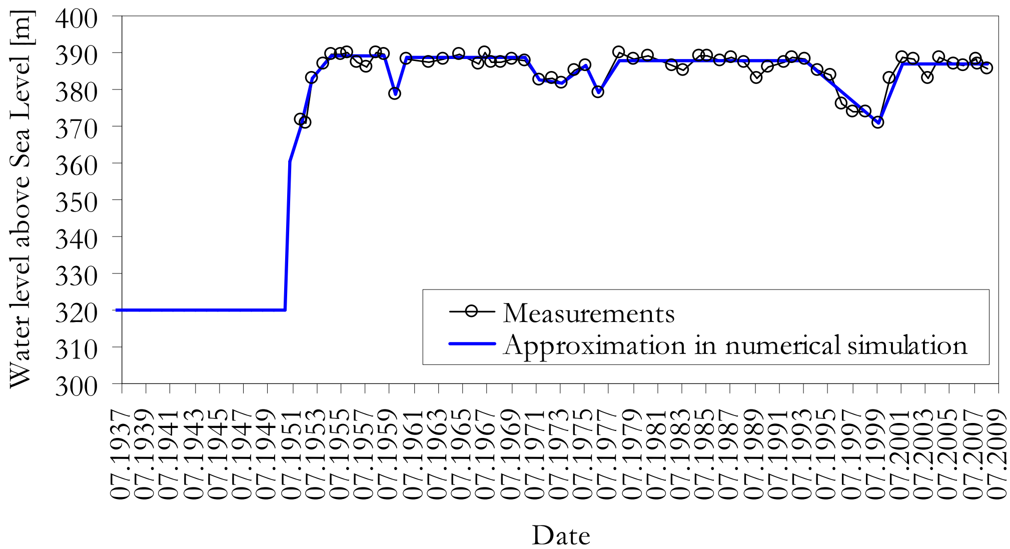

Figure 4. Measured water level in the reservoir and approximation of water level in numerical simulation

1. Construction of the dam
   The construction of the dam is divided into 15 steps and takes place over 13 years from 1938 to 1951.
2. Impounding of the dam
   The impounding of the dam takes place over 4 years from 370.80 m above the sea level to 382.84 m and then to 389.00 m above the sea level.
3. Operation of the dam
   The operation of the dam consists of the numerical simulation of significant water levels beginning from the operation of the dam up to 2009. The up and downturns of the water level measured by the Ruhrverband and the approximate water levels for the numerical simulation are given in Fig. 4.
4. Prediction
   The prediction of the deformation and the bearing capacity of the dam was predicted for 10 years using the average water level.

2.3 *Material Models and Parameters*

The used Finite Element Code provides different material models, e.g. the Mohr-Coloumb Model, the Hardening Soil Model, the Jointed Rock Model or the Soft Soil Model as well as the Soft Soil Creep Model, for the simulation of geotechnical applications.

The Mohr-Coloumb Model is a elastic-plastic material model. In the model it is assumed that the stiffness of the material (i.e. the stiffness of the soil) is constant distributed along the depth. But this is in general not the case for the material behaviour of soils. The Mohr-Coloumb Model is mostly used for numerical modelling of the mechanical behaviour of a soil in a first approach only. The following material parameters are required for the Mohr -Coloumb Model:

- Young's Modulus E
- Poisson's ratio ν
- Friction angle ϕ
- Cohesion c
- Dilatancy angle ψ

The Mohr-Coulomb Parameters as well as the saturated permeability (horizontal and vertical direction) and the soil unit weight of the soil (above and below the phreatic level) are summarized in Tab. 1. The values given in this table were determined from the Ruhrverband and were used for the numerical simulation and also used to predict other required parameters.

A more realistic material model for the simulation of the behaviour of different type of soils is the Hardening Soil Model. When soil is subjected to primary loading it shows a decrease in stiffness and irreversible plastic strains develop and in contrast to the Mohr-Coloumb Model the Hardening Soil Model includes the stress dependent stiffness behaviour of the soils, i.e. the hardening of the soil is taken into account. Besides some Mohr-Coloumb material parameters additional input parameters as the stiffness modulus E_{oed}^{ref}, unloading and reloading stiffness modulus E_{ur} (derived from one dimensional compression tests) as well as the stiffness E_{50} (derived from triaxial tests) are required for the Hardening Soil Model. All required input parameters are summarised below:

- Exponent m [-] from stress dependent stiffness power law
- Plastic straining due to primary compression E_{oed}^{ref}
- Unloading and reloading stiffness modulus E_{ur}^{ref}

Table 1. Available soil parameters determined by Ruhrverband and used for numerical simulation with Mohr-Coloumb Model

	B	CC	SB	RF	SV
γ [kN/m^3]	26	19.5	20	22	20
k [m/s]	10^{-6}	10^{-8}	10^{-5}	10^{-4}	10^{-5}
E [MN/m^2]	1000	10	50	50	50
c [kN/m^2]	3000	5	1	1	2
φ [^{o}]	37.5	28.75	33	37.5	35
ν [-]	0.3	0.4	0.4	0.3	0.4

Table 2. Soil parameters used for numerical simulation including Hardening Soil Model and Soft Soil Creep Model parameters

	B	CC	SB	RF	SV
Typ	Drained	Undrained	Undrained	Drained	Undrained
General soil parameters					
γ_{unsat} [kN/m^3]	26	19.5	18	22	20
$\gamma_{sat}[kN/m^3]$	26	19.5	20	22	20
k_x [m/d]	0.0864	0.0009	0.8643	8.6430	0.8643
k_y [m/d]	0.0864	0.0009	0.8643	8.6430	0.8643
c_{ref} [kN/m^2]	3000	5	1	1	2
φ [^{o}]	37.5	28.75	33	37.5	35
ψ [^{o}]	0	0	0	0	2
ν_{ur} [-]	0.2	0.2	0.2	0.2	0.2
Hardening Soil Model parameters					
$E_{50,ref}$ [kN/m^2]	333300	3333	16666	16666	16660
$E_{oed,ref}$ [kN/m^2]	333300	3333	16666	16666	16660
$E_{ur,ref}$ [kN/m^2]	923076	10000	50000	46153	50000
m [-]	0.5	0.9	0.8	0.5	0.5
Soft Soil Creep Model parameters					
λ [-]	–	0.030	0.006	0.006	–
κ [-]	–	0.0200	0.0040	0.0043	–
μ [-]	–	0.0012	0.0012	0.0012	–

- Plastic straining due to primary deviatoric loading E_{50}^{ref}
- Poisson's ratio for unloading and reloading path ν_{ur}
- Reference stress p_{ref}
- Cohesion c, friction angle ϕ, dilatancy angle ψ (Mohr-Coulomb Parameter)

Whereas the Harding Soil Model is not considering viscose effects as for instance creep or relaxation of a soil, the Soft Soil Creep Model takes this phenomena into account. This material model was primarily developed for the numerical simulation of deformation process of foundations or slopes. Some material parameters of the Soft Soil Creep model are related to the material parameters of the Hardening Soil Model:

- Modified compression index κ^* (derived from Hardening Soil parameters: $E_{ur}^{ref} \approx 2p^{ref}/\kappa^*$)
- Modified swelling index λ^* (derived from Hardening Soil parameters: $E_{oed}^{ref} = p^{ref}/\lambda^*$)
- Modified creep index μ^*
- Poisson's ratio for unloading and reloading path ν_{ur}
- Stress ratio in a state of normal consolidation $\sigma'_{xx}/\sigma'_{yy}$ - K_0^{NC}
- Parameter M

In a first step the numerical simulation was carried out using the Hardening Soil Model, because this model includes stress dependent stiffness and may differ between loading, reloading and unloading of the soil. In case of the Versetal dam the reloading and unloading of the soil is mainly caused by the changes of the water level in the Verse reservoir.

But the deformation measurements along the dam performed by the Ruhrverband Essen show ongoing, continuous deformations since the operation of the dam in 1955 until 2009. That is after the consolidation of the dam (the numerical simulations using the Hardening Soil Model show, that the excess pore water pressure in the cohesive soil layers were reduced to zero after the construction of the dam) deformations are not finished yet. It seems that ongoing deformations are caused by a stress redistribution due to the cyclic loading of the water level changes. Additional explanation is given by breakage of gravel due to cyclic infiltration in inherent micro-cracks. This phenomenon was approximated in further numerical simulations by using analogues Soft Soil Creep Model.

All construction phases of the dam, the phases of the impounding of the dam as well as the operation of the dam were calculated as "Consolidation Analysis" stepwise using "Staged Construction" in PLAXIS with the time intervals accordingly.

3 SENSITIVITY ANALYSIS

To evaluate the importance of model parameters (e.g. geometry, material parameters) and their influence of the results of the numerical simulations (e.g. deformations, displacement) sensitivity is carried out. In the sensitivity analysis the value of one model parameter or several model parameters are changed and its or their influence on the target value is derived (i.e. the target value is overestimated or underestimated).

In geotechnical applications sensitivity analysis is a tool to identify the value and the type of influence of material model parameters (e.g. stiffness, permeability, shear strength) to selected soil properties. Also the sensitivity analysis is used to determine the material parameters, that may be identified based on the set of available data or measurements (e.g. field measurements or laboratory measurements).

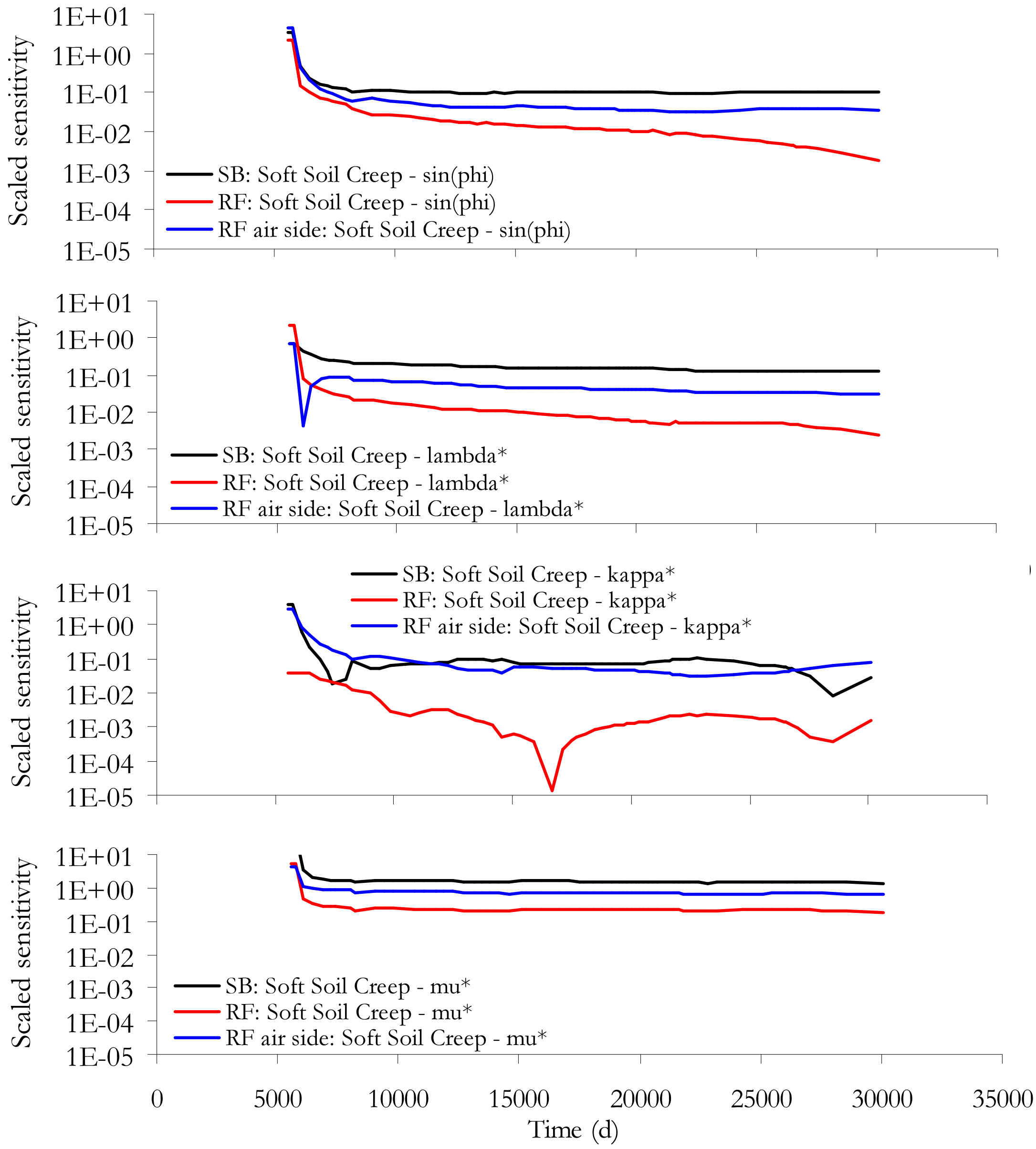

Figure 5. Scaled sensitivity (SS^{+}) of material parameters relating to vertical deformation in P11

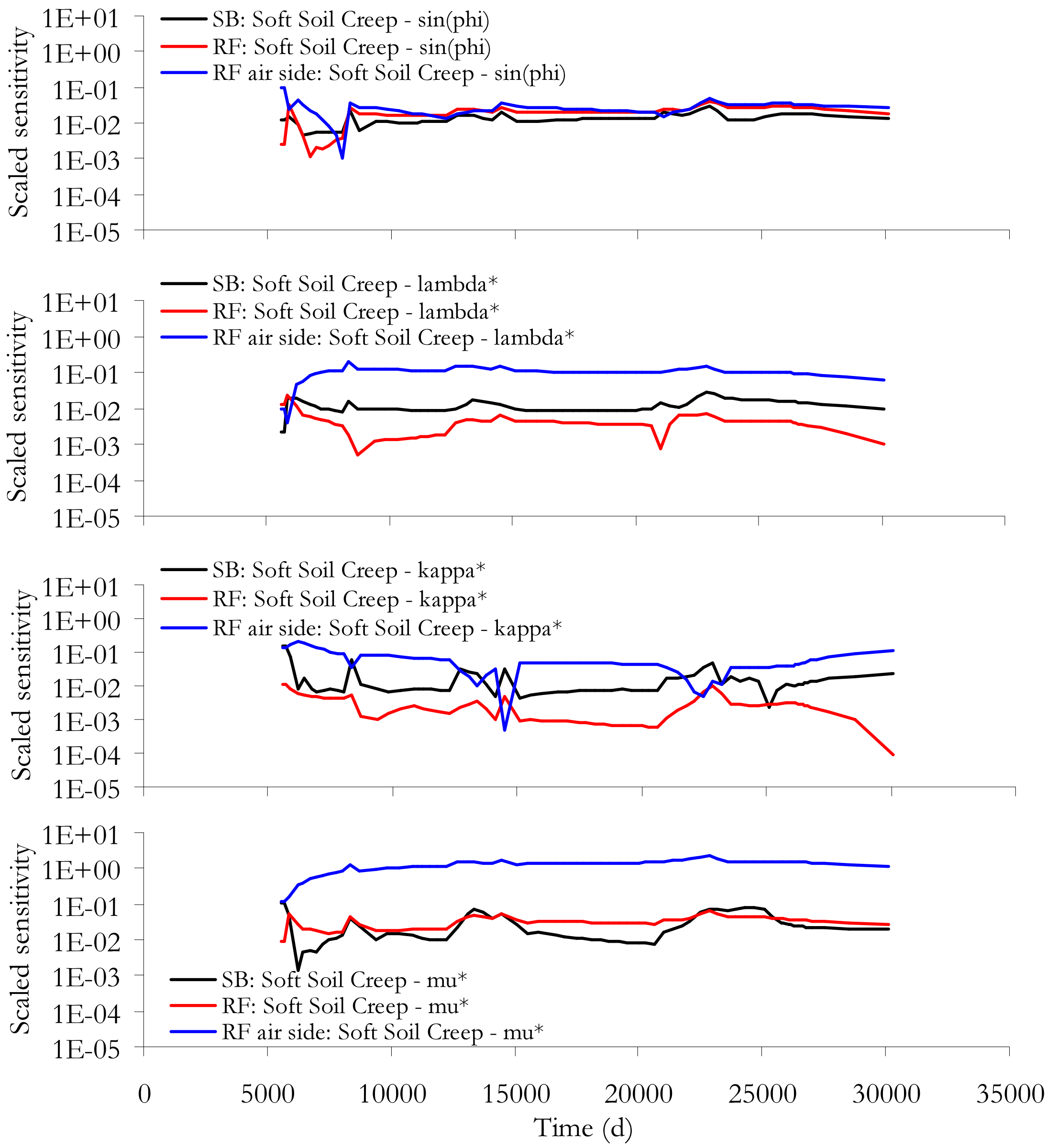

Figure 6. Scaled sensitivity (SS^+) of material parameters relating to horizontal deformation in P3003

In this study sensitivity was analyzed using a normalized scaled sensitivity analysis SS^+. The normalized scaled sensitivity analysis indicates the amount of information provided by the i-th observations y_i for the estimation of j-th parameter d_j according to Eq. 1

$$\mathbf{SS}^+ \text{ with the elements } ss^+_{i,j} = \frac{d_j}{y_i}\frac{\partial y_i}{\partial d_j}. \tag{1}$$

The results of the sensitivity analysis for the sensitivity of the Soft Soil Creep parameters λ, κ, φ and μ of the sealing body, the clay core and the rock fill (at the water side and the air side) are given in Figs. 5 and 6. The results of the calibrated results were compared to the vertical and horizontal deformations measured in the points P11 and P3003.

The sensitivity results according to the vertical deformations in P11 (see Fig. 5) show, that the material model parameters λ, κ, φ and μ of the sealing body have the most significant influence on the mechanical behaviour (i.e. vertical deformations) followed by the rock fill (at the air side). The influence of the creep index μ is most important.

The sensitivity results according to the horizontal deformations in P3003 (see Fig. 6) show, that the material model parameters λ, κ, φ and μ of the rock fill (at the side of the air) have the most significant influence on the horizontal deformations. The most important influence was found for the creep index μ.

4 MODEL CALIBRATION

In the actual case the model calibration is done by using inverse analysis and optimisation procedures. To use optimisation procedures or algorithms we need a definition of the objective function $F(\mathbf{d})$ with the unknown model parameters $\mathbf{d}$.

4.1 *Objective Function*

In physics or engineering optimisation methods are used to interpret measurements from field or laboratory tests by changing constitutive material model or geometry model parameters of an analytical or numerical boundary value problem. The parameter modification is done until the model results fit the experimental data. The quality of the fit can be expressed by the squared sum of all differences $f_i(\mathbf{d})$ between the numerical model $y_i(d_1, d_2, \dots, d_n)_{calc}$ and the experimental data $y_{i_{meas}}$ e.g.

$$f_i(\mathbf{d}) = y_{i_{meas}} - y_i(d_1, d_2, \dots, d_n)_{calc}. \tag{2}$$

and

$$F(\mathbf{d}) = \frac{1}{n} \sum_{i=1}^{n} f_i^2(\mathbf{d}) \omega_i. \tag{3}$$

A more advanced formulation can be found by scaling the squared differences $f_i(\mathbf{d})$ with the mean squared value of all observations

$$F(\mathbf{d}) = \sqrt{\sum_{i=1}^{n} \frac{f_i^2(\mathbf{d})}{\sum_{j=1}^{n} y_{i,meas}^2} \omega_i}. \tag{4}$$

Here

F: is the value of objective function
$i = 1, \dots, n$ number of measurements in each test series
ω: factor of weighting

Basically the objective function can be any formulation describing somehow the quality of the calibrated model. A weighting of single measurements can be done using the weighting factor ω_i.

4.2 *Inverse Analysis and Model Calibration*

Mathematically an optimisation problem (minimisation problem) can be described as follows:

Given: an objective function F in a parameter search space D of real numbers $\mathbb{R}$ ($F : D \rightarrow \mathbb{R}$).
Sought: one element or model parameter vector (e.g. $\{E, \varphi, c, \dots\}$) $\mathbf{d}_0$ in D,
for which Function $F(\mathbf{d}_0) \leq F(\mathbf{d})$ for all $\mathbf{d}$ in D ("minimization-problem"), in the optimal case $F(\mathbf{d}) \rightarrow 0$ for $\mathbf{d} \rightarrow \mathbf{d_0}$

The optimisation can be done using either gradient procedures or evolutionary algorithms.

In this case we used the well known particle swarm algorithm (Kennedy & Eberhard 1995) together with a surrogate model

$$y(\mathbf{d})_{calc} = \hat{y}(\mathbf{d}, \beta) + \hat{\varepsilon} \tag{5}$$

for the Versedam in which the numerical finite element model is approximated by fully quadratic formulations $\hat{y}(\mathbf{d}, \beta)$ for each time step t in Points 11 and 3003. β are the coefficients for a fully quadratic approximation, $\hat{\varepsilon}$ indicates the error between the finite element model and the surrogate model.

Based on the information of the soil investigation report, due to the lack of information regarding the creep index μ of the sealing body and the rock fill and due to the high sensitivity of the creep index μ on the numerical model response (see figures 5 and 6) we focused on the calibration of the creep index μ and selected the stiffness and friction parameters from the soil investigation report.

The objective function is created using equation (4) for each measurement series and summed to

$$F_{total}(\mathbf{d}) = \frac{1}{m}\sum_{j=1}^{m} F_j(\mathbf{d}) \tag{6}$$

with $j = 1, \ldots, m$ number of test series.

Two cases have been analysed to verify the influence of number of available test data on the quality of the calibrated numerical model. Case one considers only the vertical settlements in point

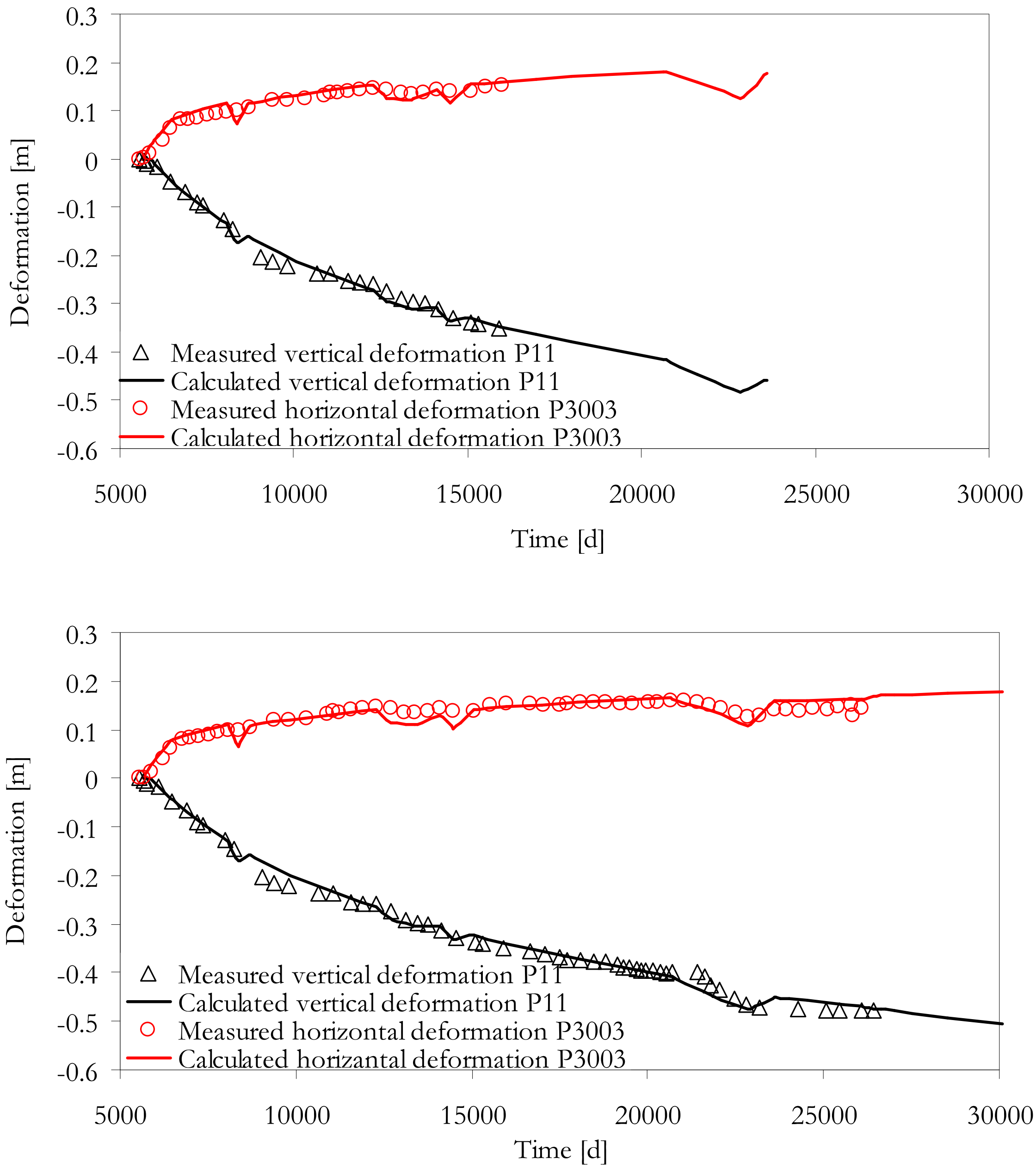

Figure 7. Comparison of vertical and horizontal measured results and calculated results in Point 11 and 3003

Table 3. SSC parameter resulting from optimisation, stability (factor of safety) and prediction of deformation

Variation	V1-HV	V2-HV	trend
Observations used until	1980	2009	
SB μ^* [-]	0.001546833	0.001661657	↗
RF μ^* [-]	0.000859106	0.000723486	↘
Msf (ignore undrained behavior (D)) [-]	1.62	1.60	↘
Msf (undrained (UD)) [-]	1.39	1.39	→
u_y P11 [m] at t=30.000 d	-0.515	-0.506	↗
u_x P3003 [m] at t=30.000 d	0.205	0.168	↗

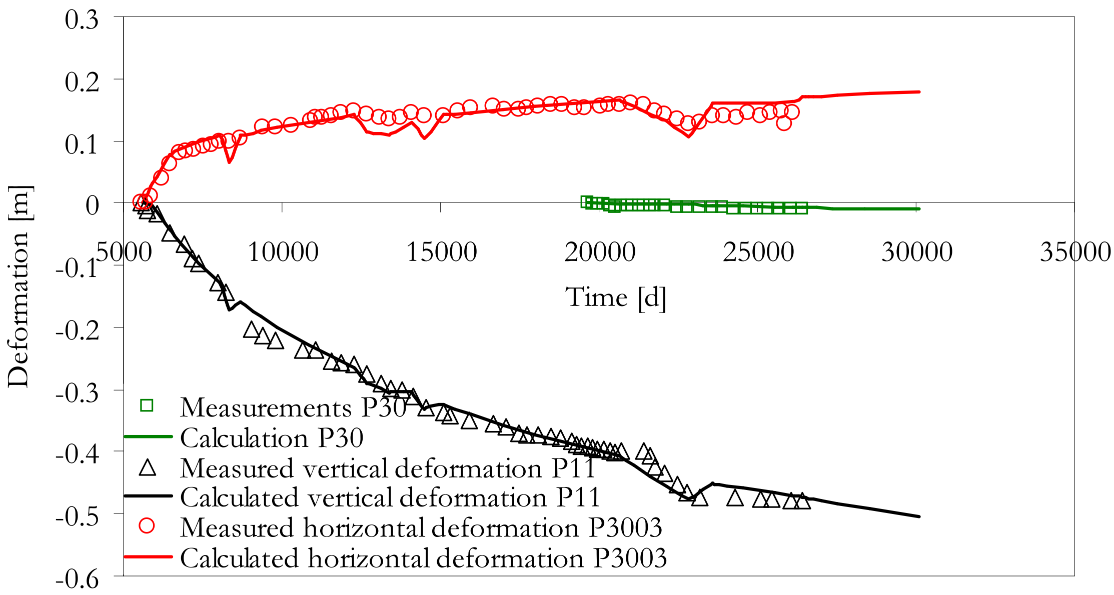

Figure 8. Comparison of vertical and horizontal measured results and calculated results in Point 11, Point 3003 and Point 30

11 and the horizontal deformation in point 3003 until the year 1980, the second case considers these recordings until 2009. Both calibrated models have been compared in table 3.

To validate the calibrated model the desired model responses in P11 and P3003 are plotted together with the calculated and measured deformation in P30 which has not been part of the objective function in equation (4) and (6). Figure 8 shows excellent agreement between the numerical model and the field measurements. Both calibrated creep indices μ have marginal differences in Variations V1 and V2 and no influence on the factor of safety Msf (see table 3).

5 INFLUENCE OF THE ERROR OF OBSERVATION ON THE PREDICTION OF THE FACTOR OF SAFETY MSF

In finite element calculation the factor of safety Msf is calculated by reducing the shear strength parameters φ and c until a minimum shear strength is obtained (Brinkgreve et al. 2002)

$$\sum \mathrm{Msf} = \frac{\tan\varphi_{input}}{\tan\varphi_{reduced}} = \frac{c_{input}}{c_{reduced}}. \tag{7}$$

To analyse construction and operation dependent (cycling water level) stability of the dam we evaluated the factor of safety Msf after each modelled construction stage. Figure 9 indicates, that (1) the operation of the dam (since 1952) and (2) its ongoing deformation, has no influence on the global stability. If we assume, that only the creep behaviour influences the ongoing deformation

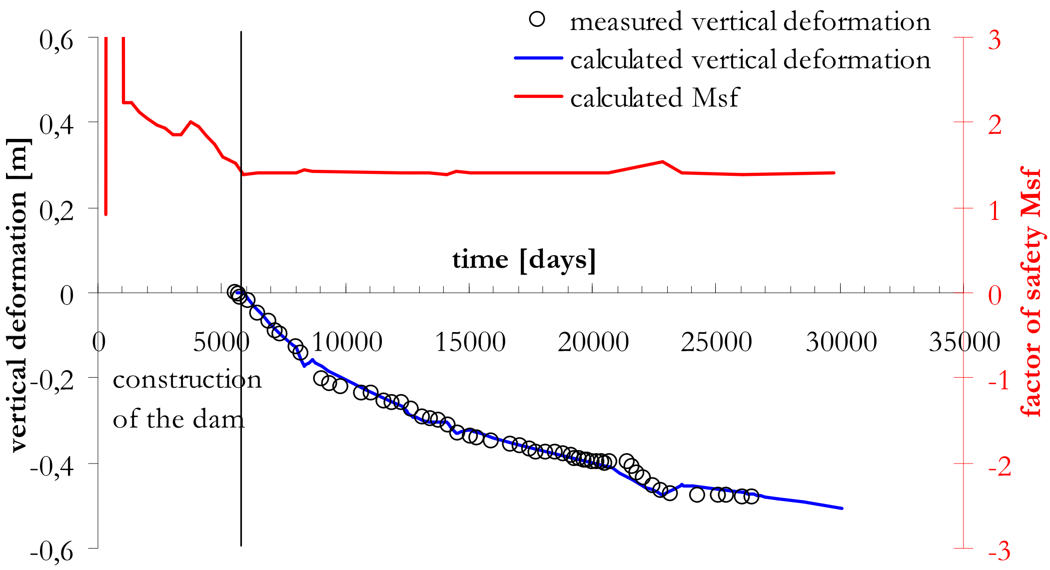

Figure 9. Vertical observations and calculated results in P11 vs. calculated Msf

and not cyclic loading and unloading conditions a closer look to equation (7) emphasises this conclusion.

To investigate if it is possible to observe the long term settlement and deformation behaviour of the dam by using GPS equipment we had to assess if we can conclude on the stability of the dam by exceeding a certain error of observation (vertical u_y or horizontal deformation u_x). Therefore we simulated material damaging in terms of reduction of the shear strength parameter φ in three possible damage zones (see Fig. 10) and evaluated (1) the corresponding factor of safety Msf and (2) the corresponding deformation u_y and u_x.

The possible error of observation for vertical and horizontal measurement equipment (e.g. GPS) has been plotted together with the calibrated model response and the measured data (Fig. 11). In this figure φ of the sealing body (2) has been reduced from today on until a minimal stability has been obtained (Msf $\leq$ 1.0). Its reduction leads to increasing vertical deformation in point 11. It has only marginal influence on the horizontal deformation in point 3003.

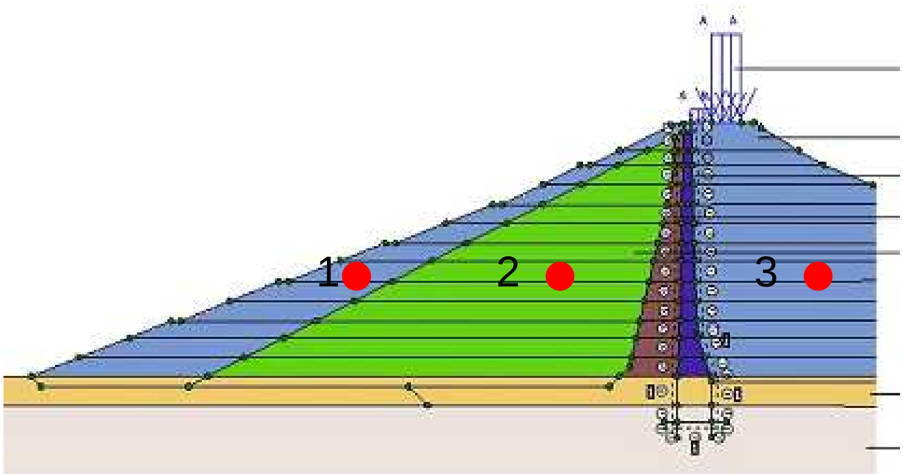

Figure 10. possible damage zones, definition and subdivision into rock fill (water side) (1), sealing body (2) and rock fill (downstream)(3)

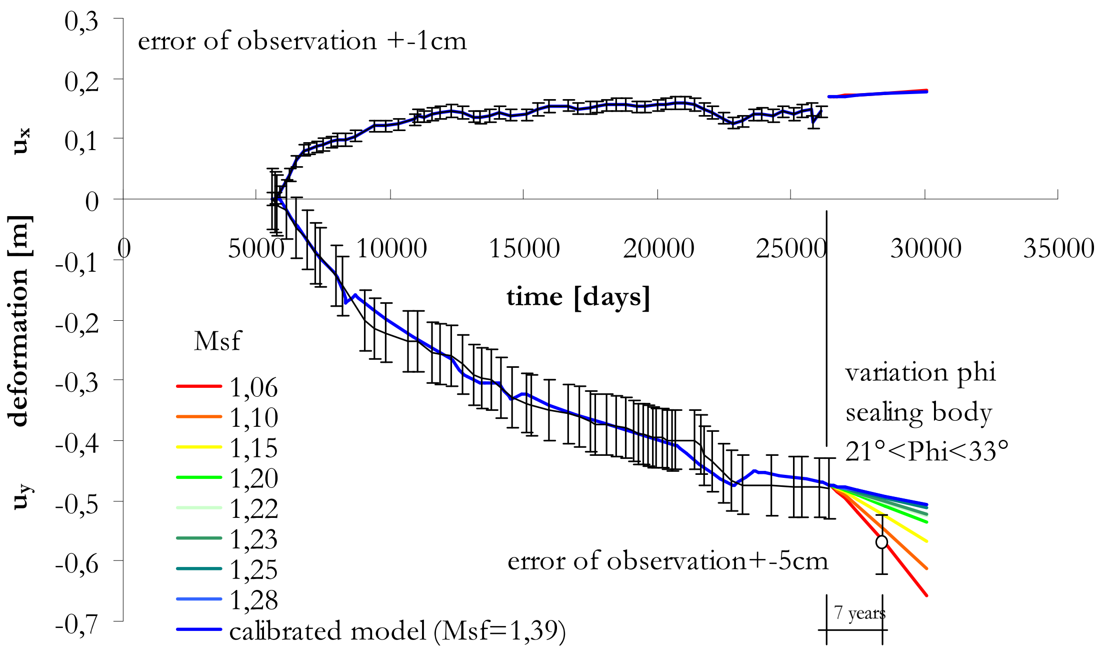

Figure 11. Calculated vertical and horizontal deformation, possible error of observation and factors of safety Msf for varying φ of the sealing body

Taking into account a possible error of observation (±5cm for vertical GPS recordings), after minimum seven years we could conclude on some damage in the dam that could lead to stability problems (failure).

6 CONCLUSIONS

To assess the influence of the error of observation on the determination of the stability of the Versedam it was essential to identify in situ soil material model to simulate the real deformation behaviour of the dam.

The primary used material models ”Mohr Coulomb” or ”Hardening Soil” for the Versedam construction (except the concrete core) were not able to simulate ongoing deformations due to viscouse soil-fluid interaction and creep behaviour due to internal stress relocation caused by oscillating water levels. It is suggested to use a constitutive model which considers creep as an analog.

In the demonstrated example of the Versedam model, the finite element method, together with the soft soil creep model, is appropriate to simulate the observed vertical and horizontal deformation.

The calibration of the numerical model of the dam has been done using the Soft Soil Creep Model. The vertical deformation observations of point 11 and the horizontal deformation observations in point 3003 have been part of the objective function. For the calibration the particle swarm algorithm has been used. To accelerate the optimisation procedure the numerical finite element model has been replaced by a fully quadratic approximation (surrogate model) in Points 11 and 3003.

With the observations until 1980 we succeeded in calibrating the numerical model. Using the observations until today only leads to marginal improvement.

Analysing the influence of the error of observation on the prediction of the stability shows that it is not possible to conclude on the stability if the error of observation measurement is large (e.g. vertical GPS measurement) compared to the expected increasing deformation.

To assess if the locations of observations can be improved such that it is possible to conclude on the stability of the structure it is recommended to analyse the numerical model using a node-based sensitivity analysis (Schanz et al. 2007, Zimmerer 2010).

7 ACKNOWLEDGEMENT

The sensitivity and inverse analysis has been performed using the inhouse software VARO^{2}PT of VAROCON. For further details contact info@varocon.com.

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